# Recent Advances in the Development of the VASIMR Engine


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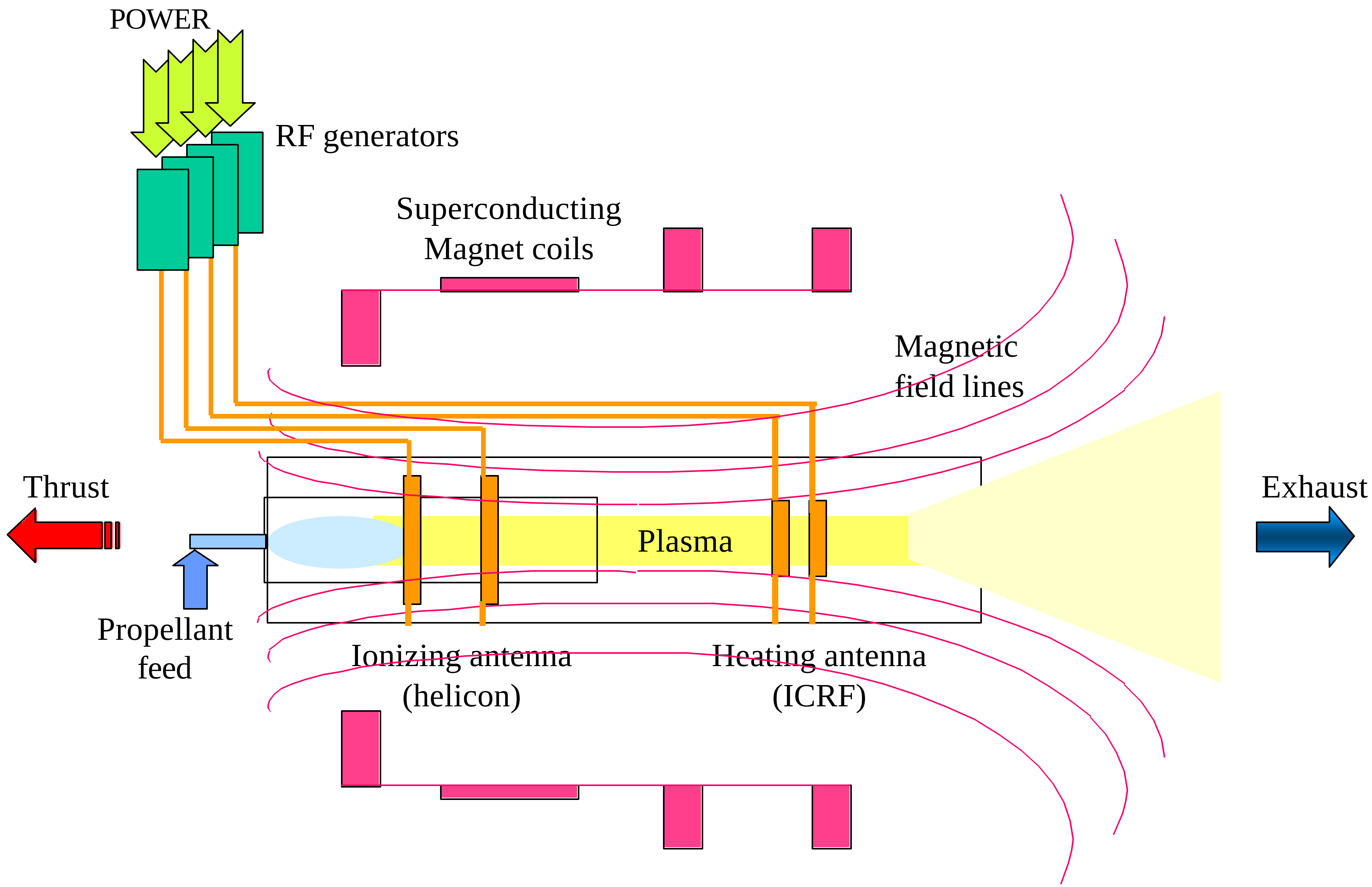
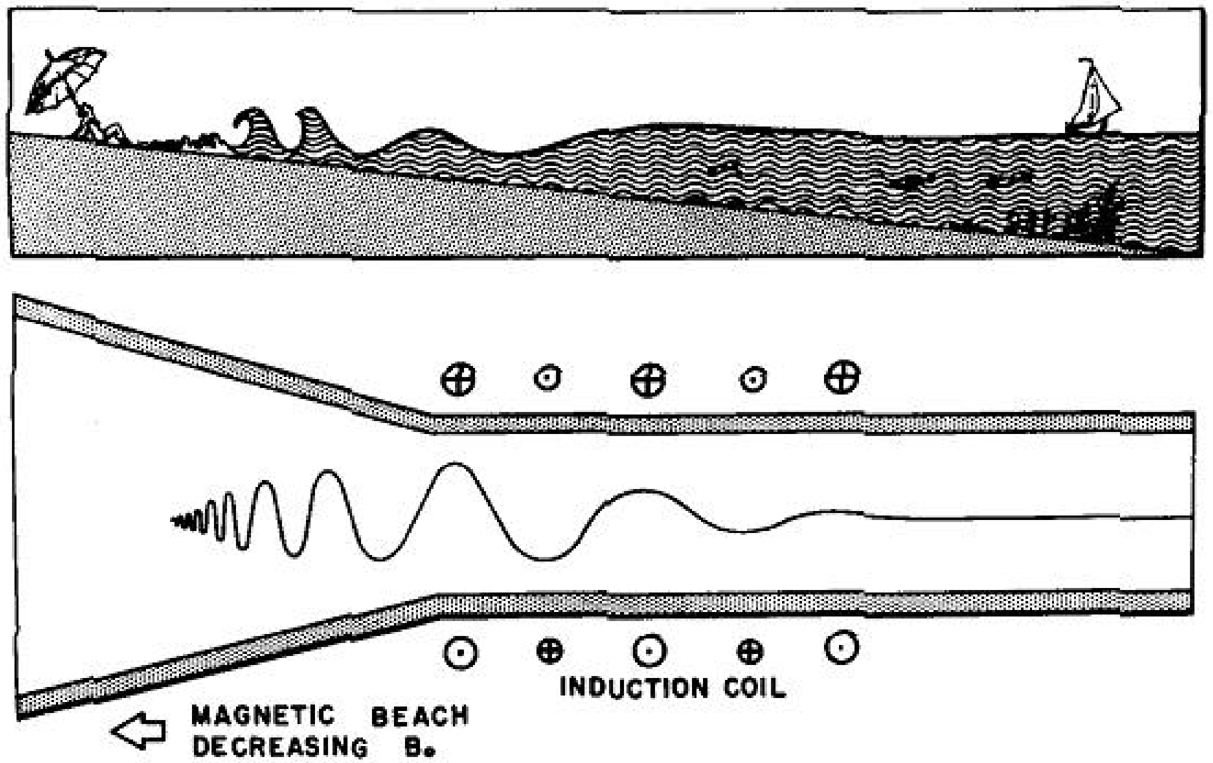
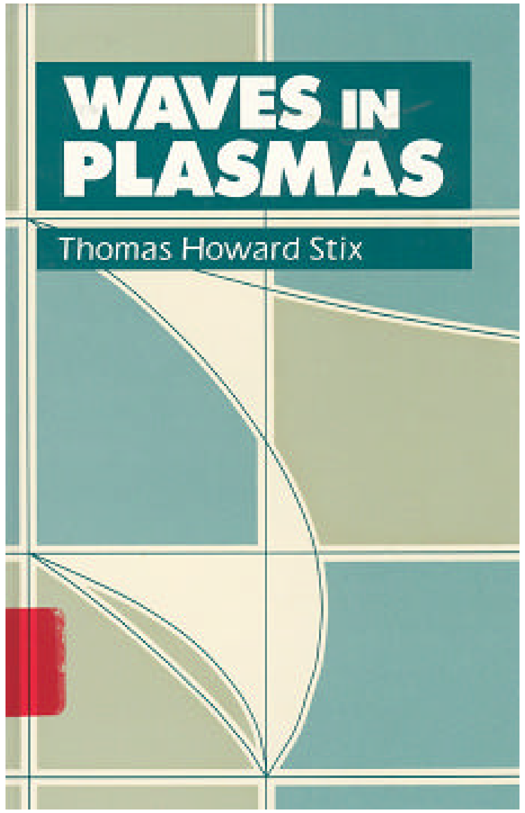
# Simplified Diagram of VASIMR Thruster



# Magnetic beach concept introduced by H. Stix




- *Particles gain energy from the incident wave, like surfers on the ocean*
- *Mechanism is proven very efficient in fusion plasmas*

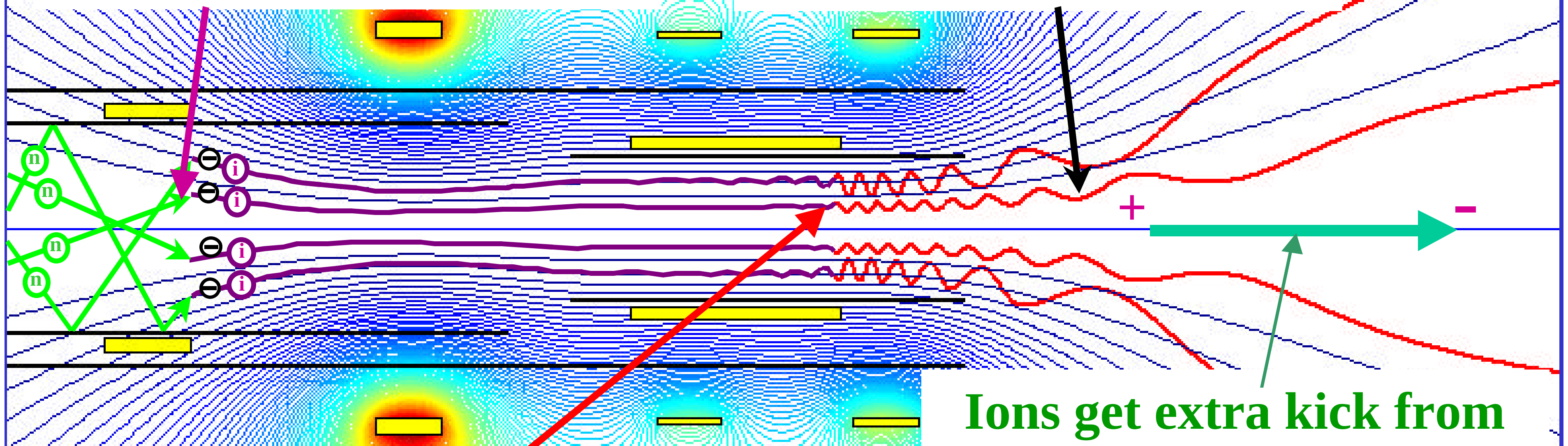
# Physics of VASIMR

### Plasma Source

RF waves establish a “helicon” discharge, which ionizes neutral gas to produce a dense plasma with an electron temperature of a few eV

### Magnetic Nozzle

When particles see an expanding magnetic field, they are accelerated axially at the expense of their rotational motion.



### ICRF heating

**(Ion Cyclotron Range of Frequencies)**

Injected electromagnetic waves accelerate the ions by resonating at magnetic beach with their fundamental cyclotron frequency (and associated harmonics.)

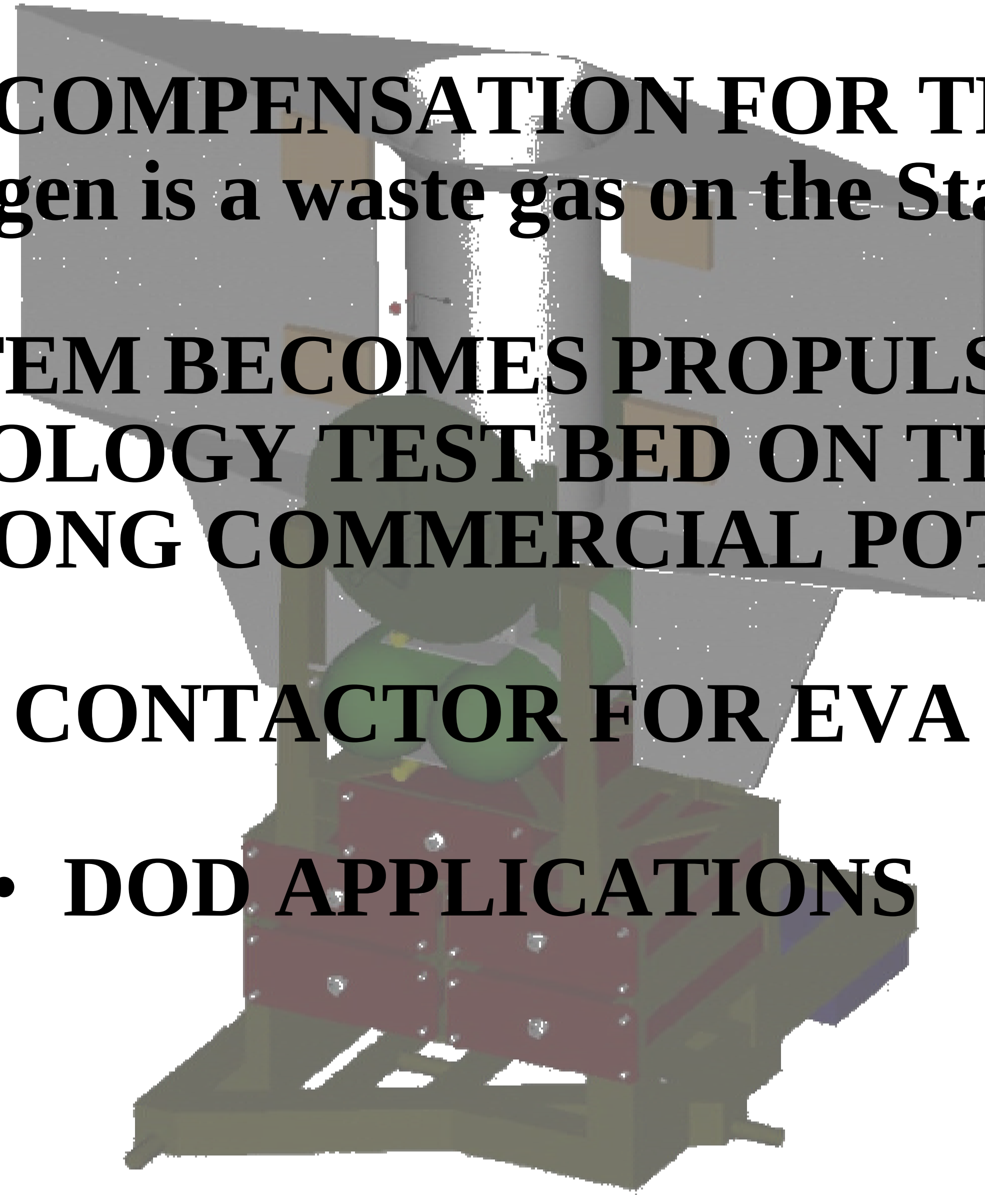
**Ions get extra kick from ambipolar electric field**

**Both ions and electrons leave at the same rate**

# Important Advantages

- No electrodes or other materials in direct contact with the plasma.
- Therefore, potential for very high power density, high reliability, long life.
- Multiple propellants: Helium, Hydrogen, Deuterium, Nitrogen, Argon, Xenon, others…

# NEAR TERM BENEFITS



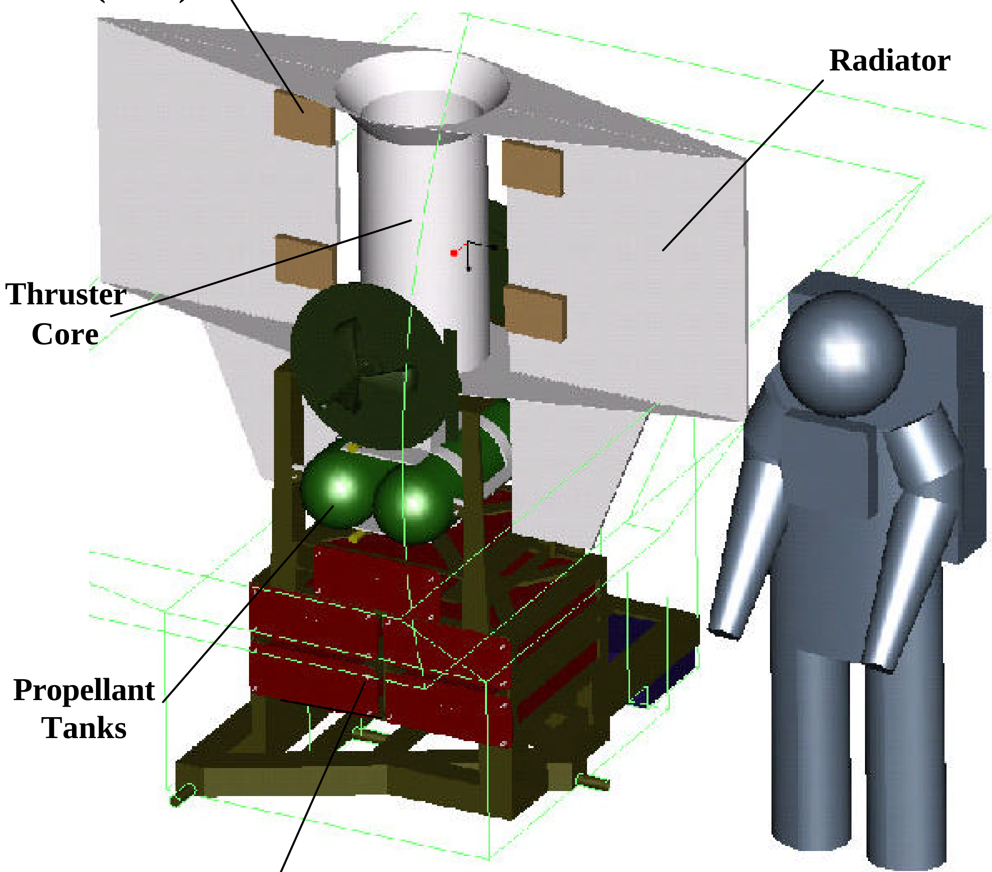
• DRAG COMPENSATION FOR THE ISS (Hydrogen is a waste gas on the Station)

• SYSTEM BECOMES PROPULSION TECHNOLOGY TEST BED ON THE ISS WITH STRONG COMMERCIAL POTENTIAL

• PLASMA CONTACTOR FOR EVA SAFETY

• DOD APPLICATIONS

# VASIMR Demonstration on ISS

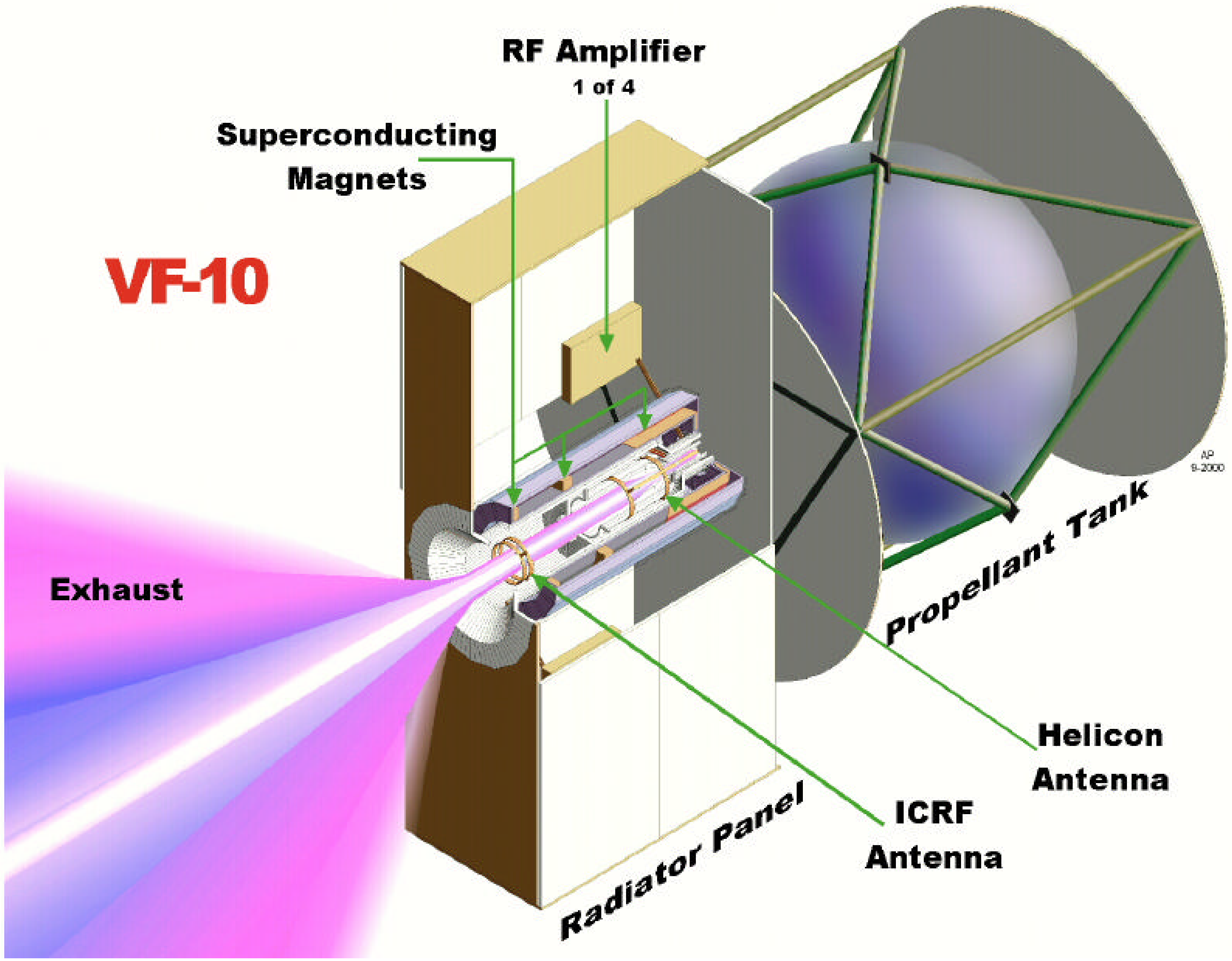



Approximate Dimensions
of Thruster Core:
Diameter < 0.5 m
Length < 1 m

**Stepwise Approach:**

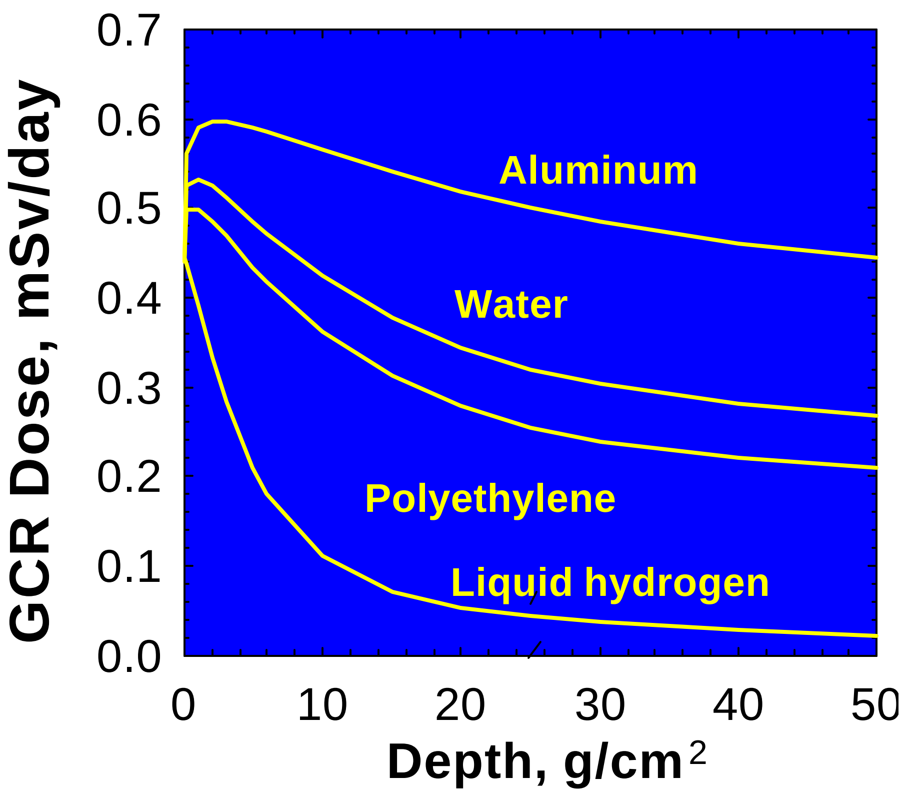
- **Design, build, and test experimental VASIMR thruster in ground test facility and demonstrate performance.**
- **Test Operation as attached experiment on ISS.**
- **Use short ~ 10 min firings using stored power (~ 25 kW) from batteries.**
- **Minimum interfaces with Station**

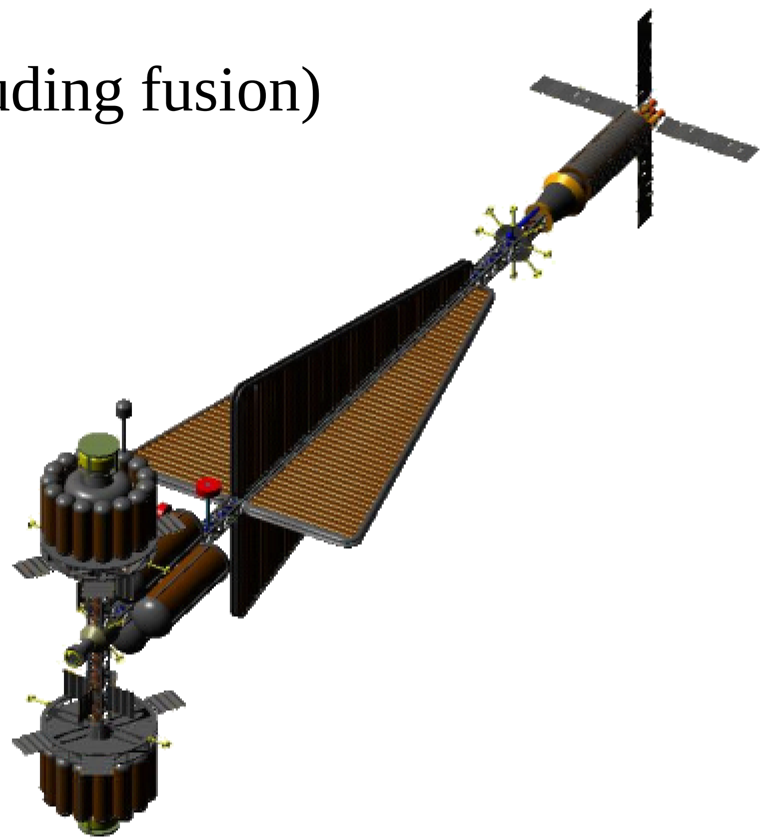
# First Generation Near Earth Free Flyer



# LONG TERM BENEFITS

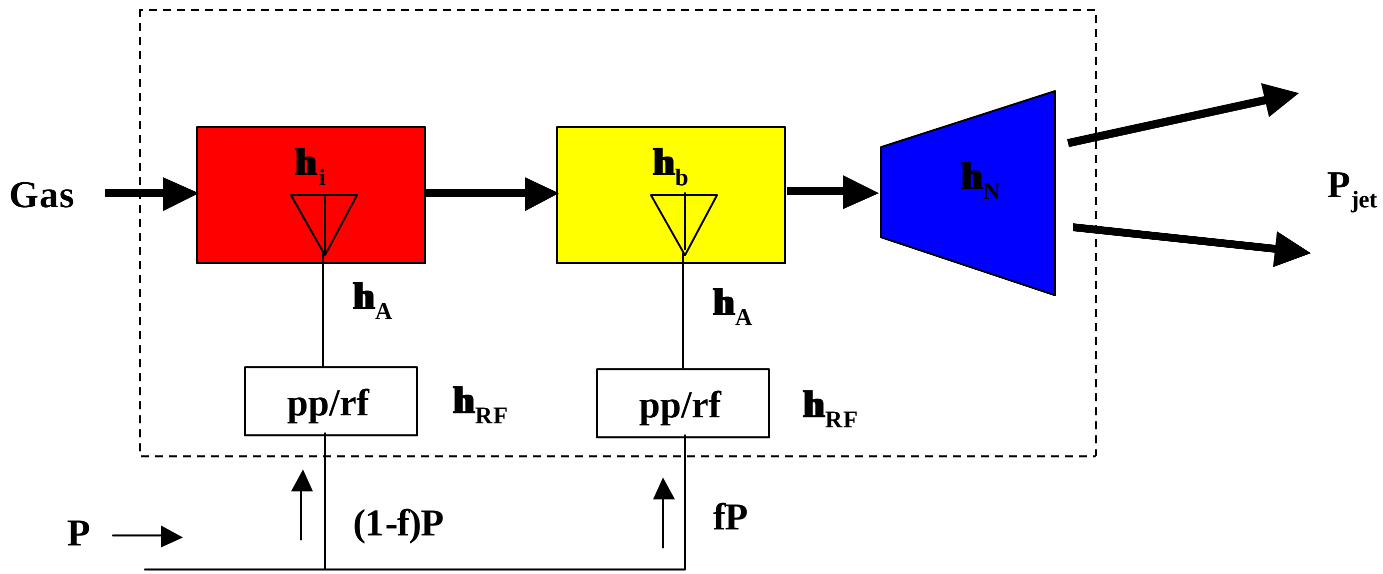
- Opens entire Solar System to very fast space transportation for humans and robots
- Major future growth potential (including fusion)



- Hydrogen propellant is plentiful, inexpensive, and best known radiation shield

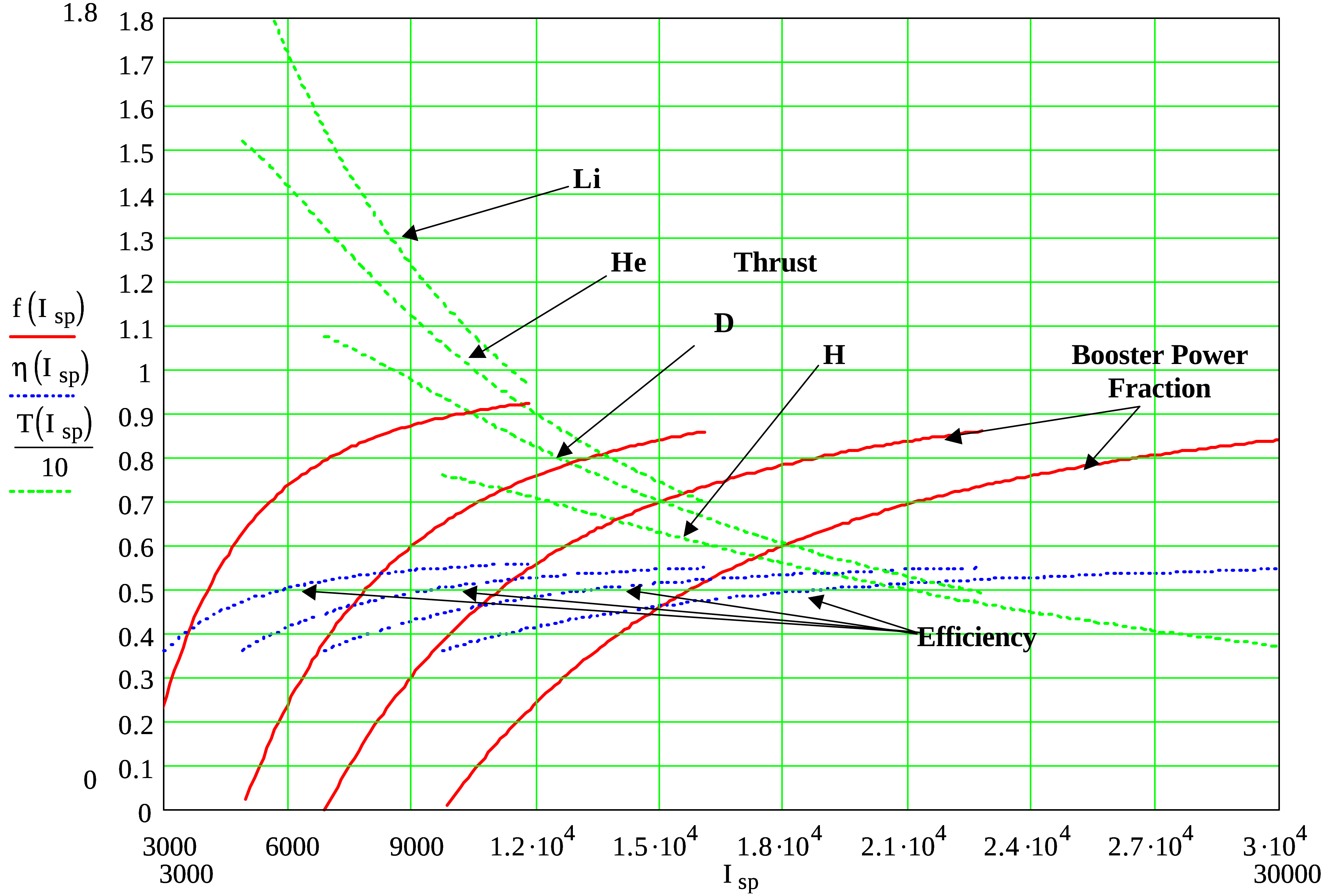
# Engine Efficiency



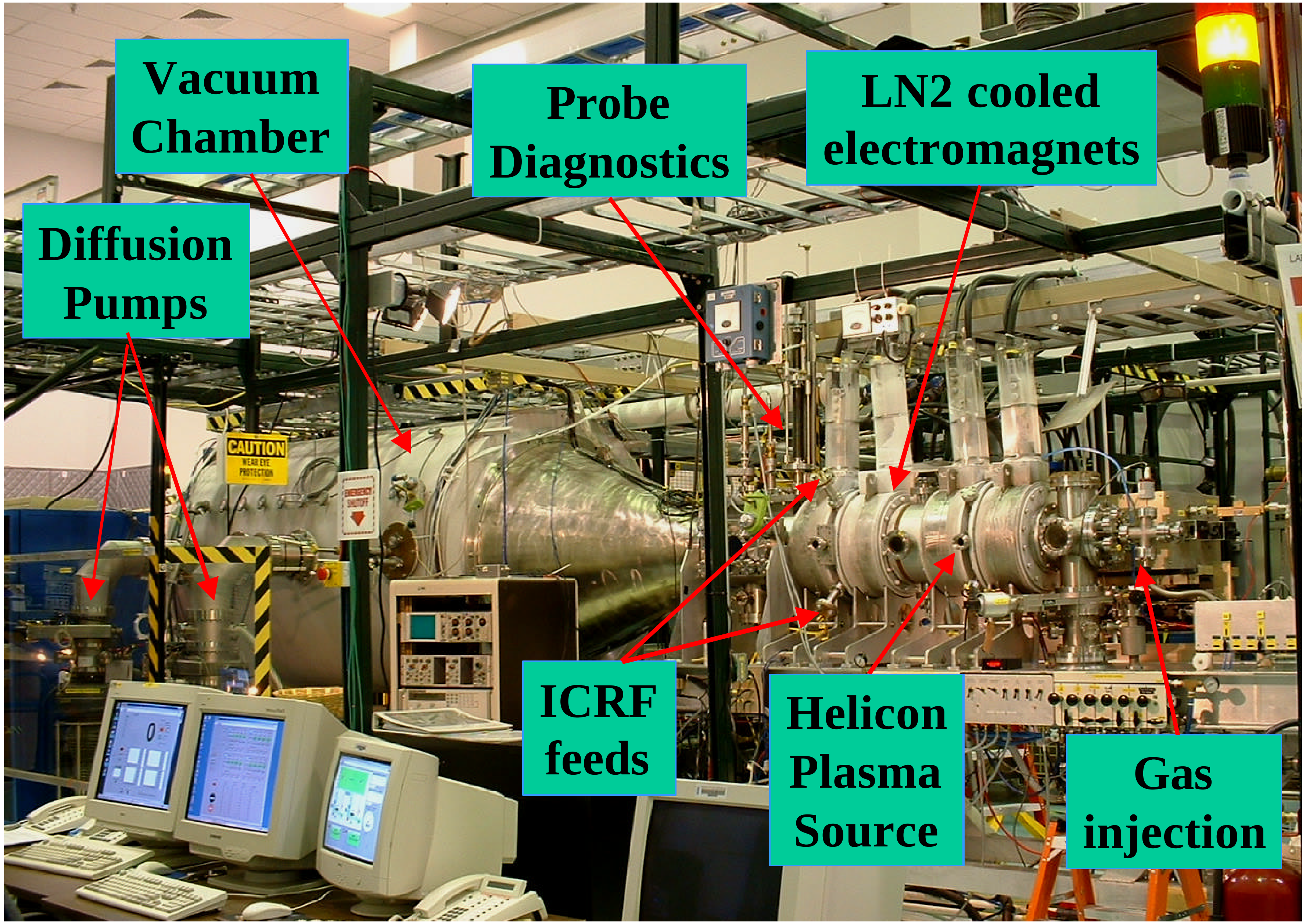

**Definitions:**

| | | | |
|---|---|---|---|
| P | DC input power to the PPU in Watts. | f | Fraction of input power to the RF booster stage |
| $\eta_{RF}$ | RF power processor unit efficiency | $\eta_A$ | Transmission line and antenna efficiency |
| $\eta_i$ | Helicon efficiency | $\eta_b$ | RF booster efficiency |
| $\eta_N$ | Nozzle efficiency | | |

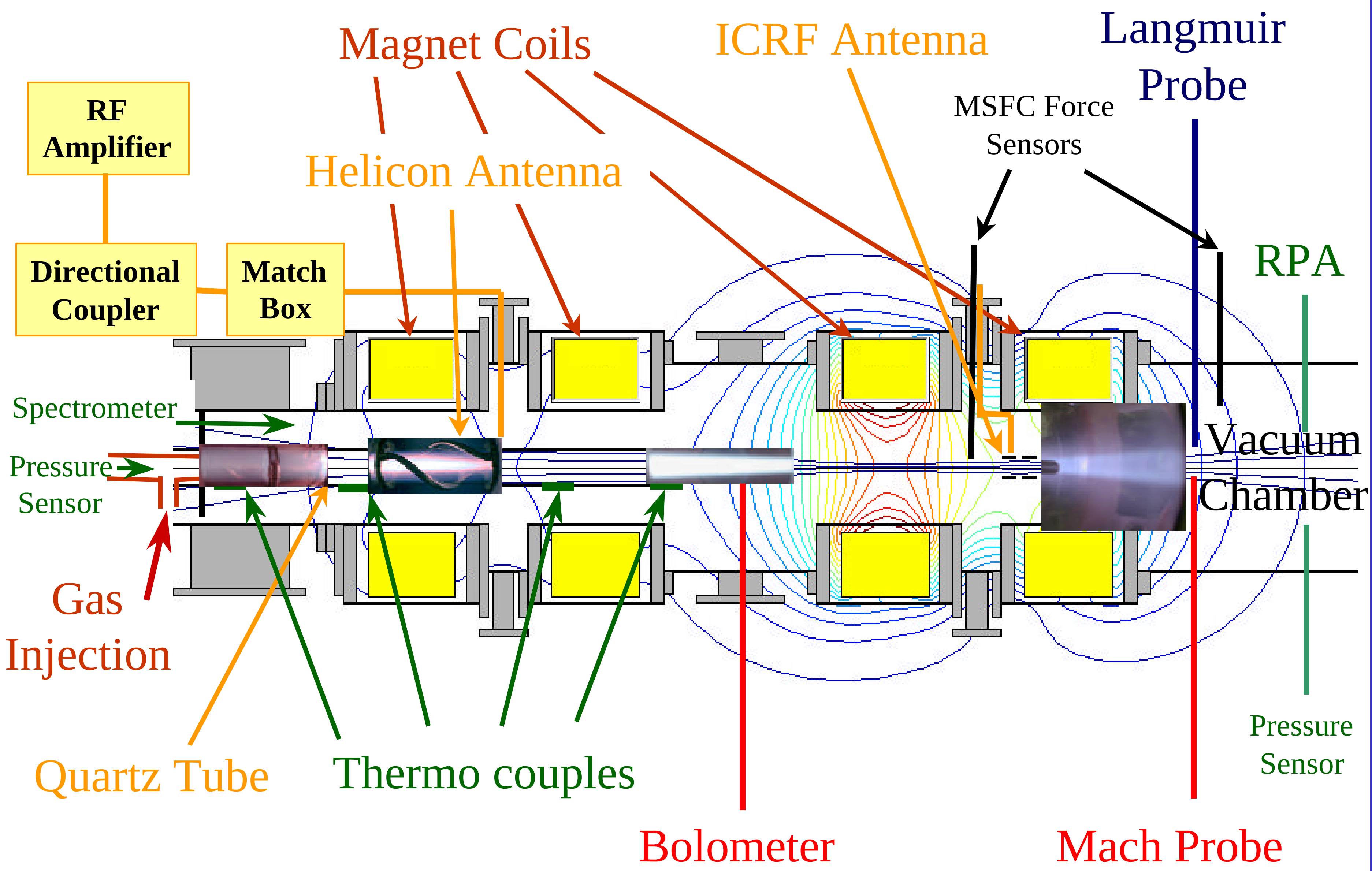
# Engine Performance Estimates with Near-term technology



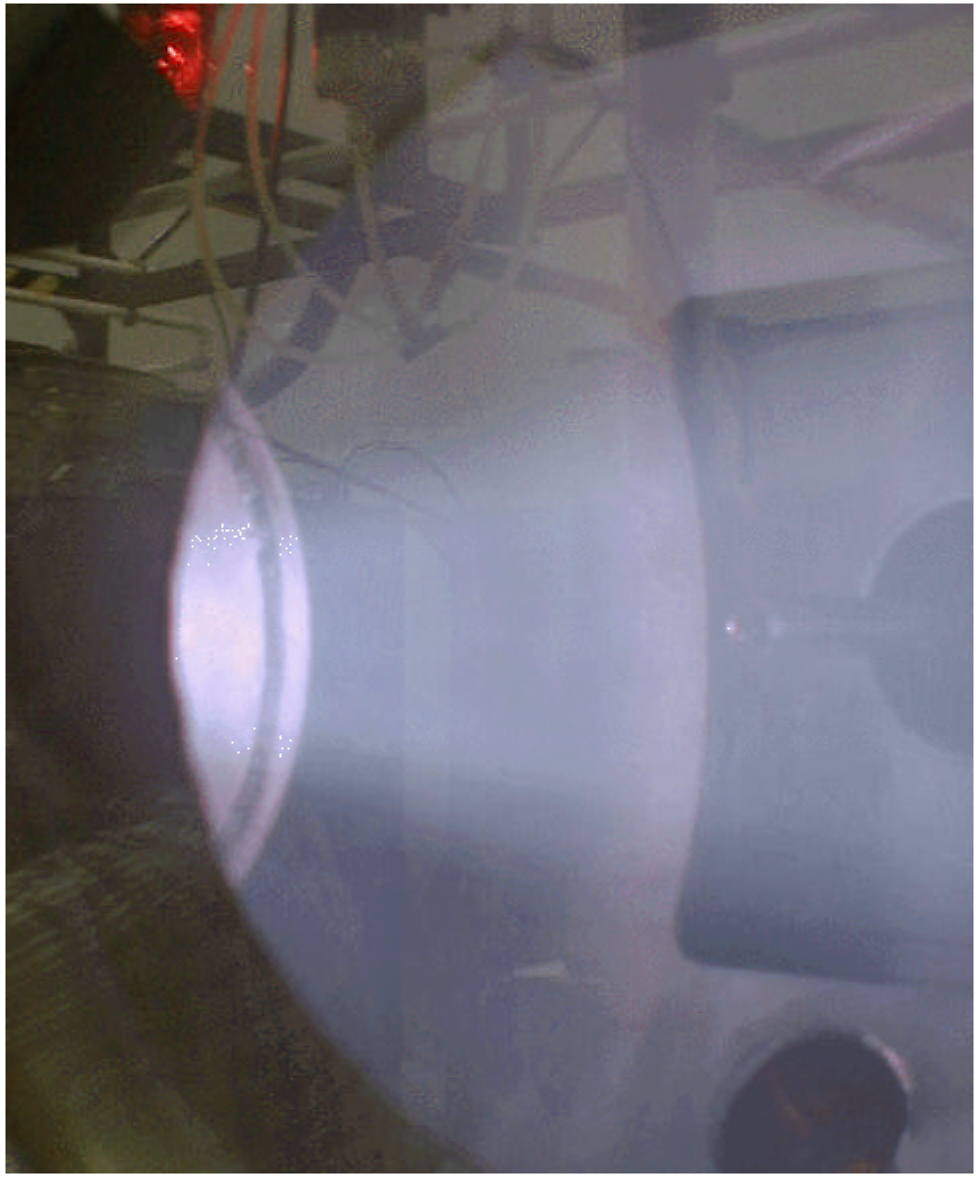
# Experiment demonstrates the physics

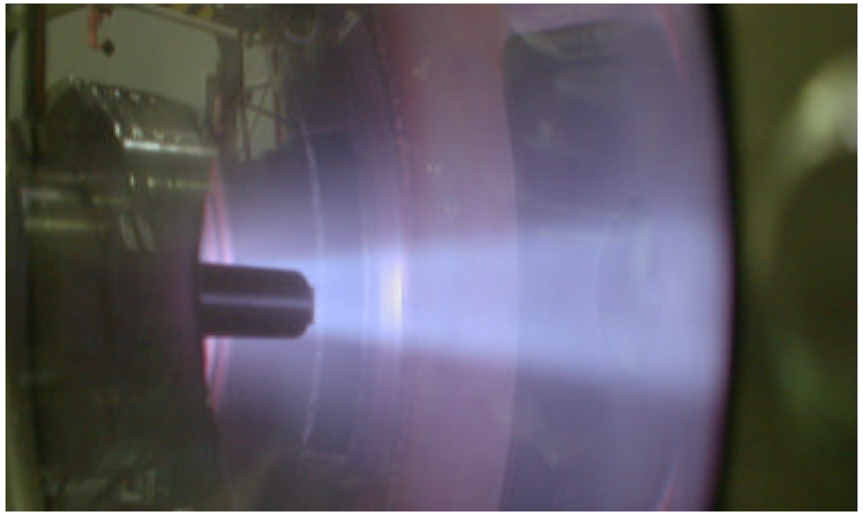


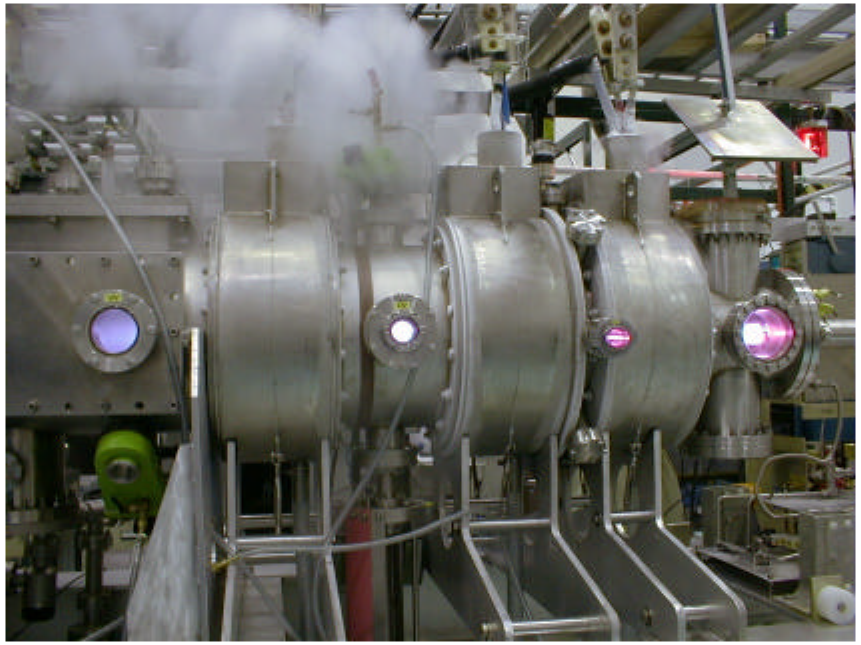
# Wide array of diagnostics cross check results



# VASIMR Hydrogen Magnetoplasma

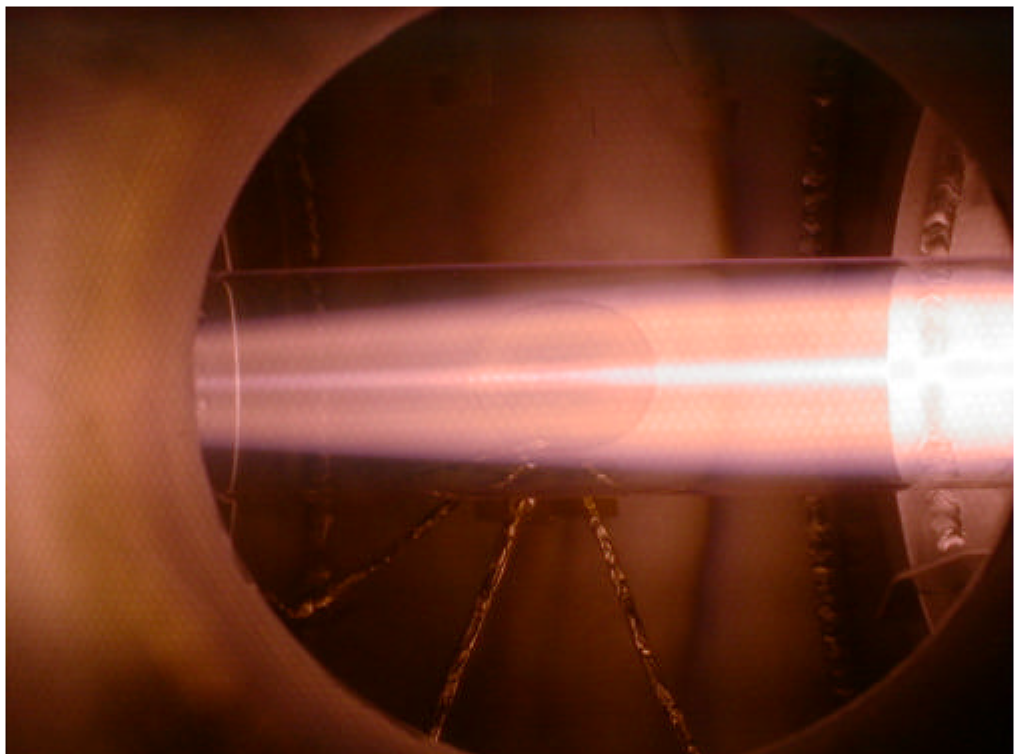


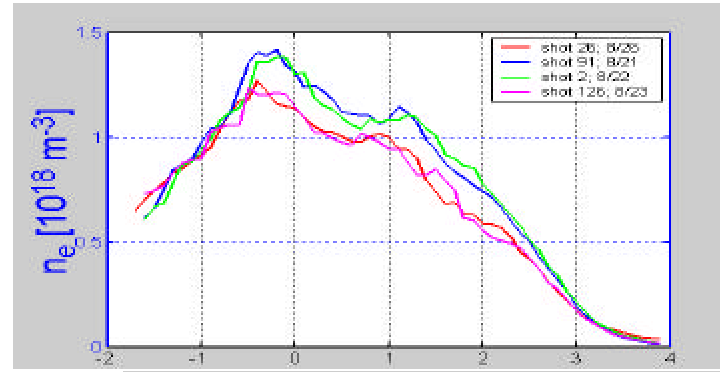


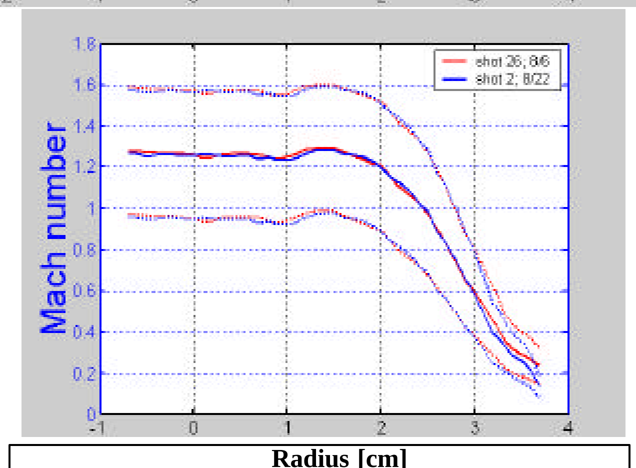


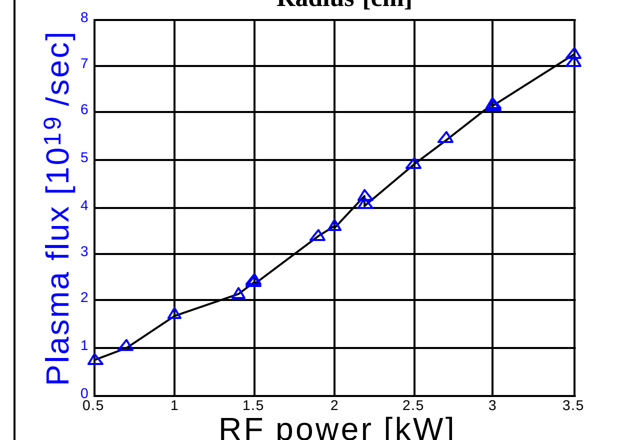
# Achieved steady-state operation with light gases

- High density, stable plasma discharges with many gases are now routine
- Plasma flows very fast
- Plasma output linear with input power





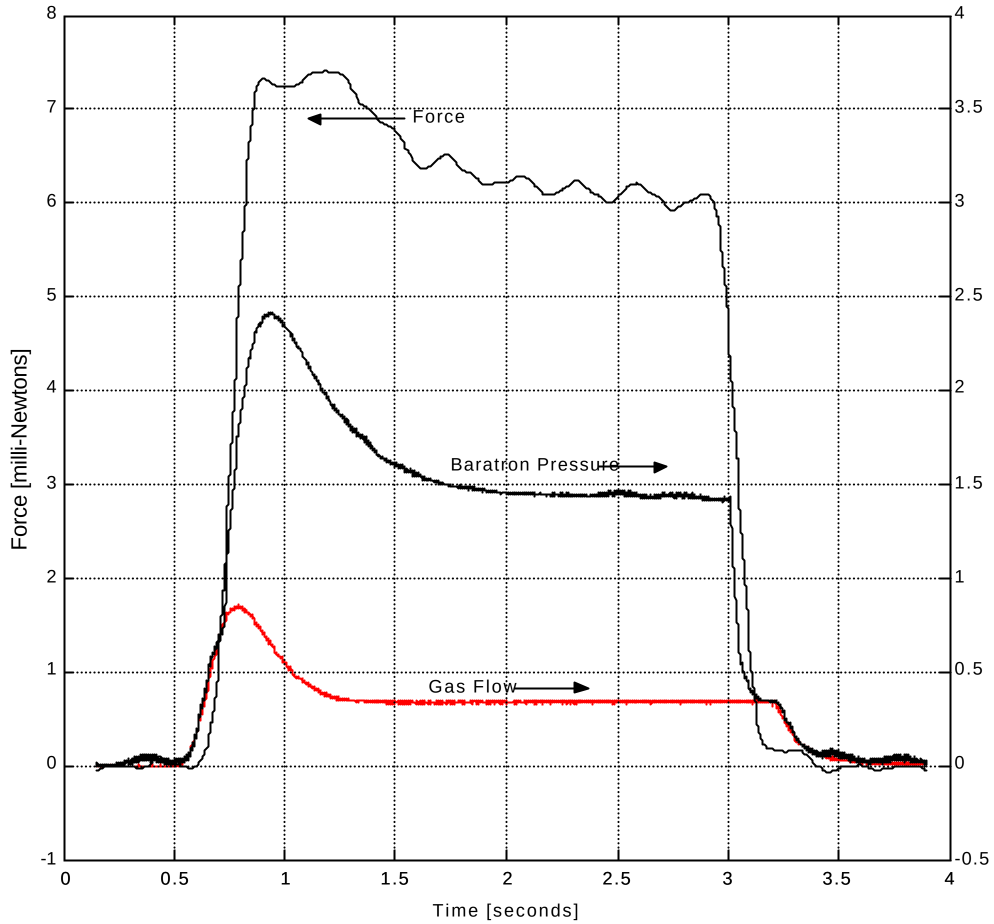
# Specific Impulse of Plasma Source

**From force measurements, the plasma source ALONE already produces a very high specific impulse. This value is likely to be higher. Measurement is biased low due to pumping limitations.**

$$Isp = \frac{T}{\dot{m}g}$$

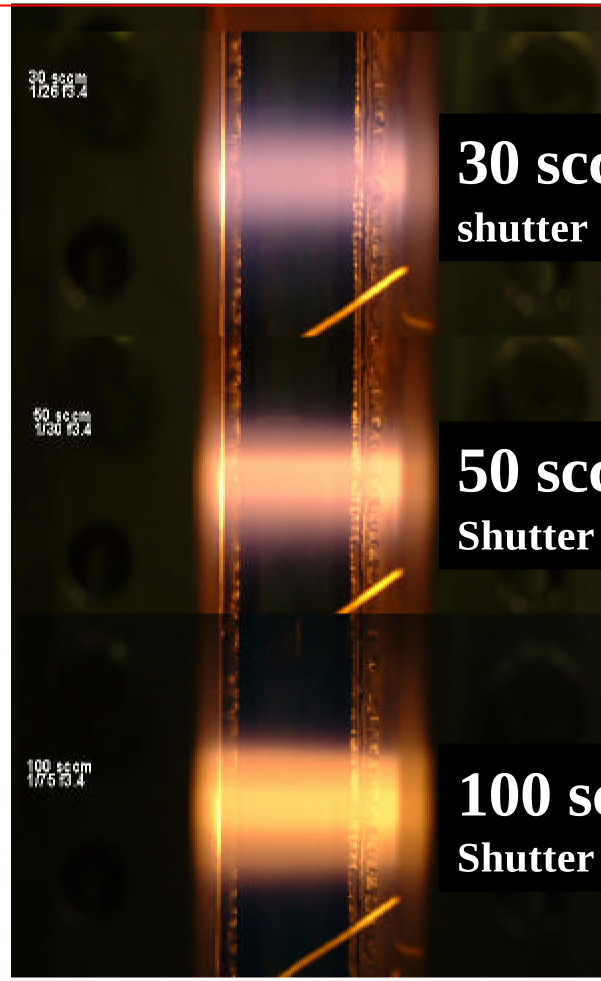
$$Isp = \frac{.006\ \mathrm{N}}{\left(3\times10^{-7}\ \mathrm{kg}/\mathrm{sec}\right)\left(9.8\ \mathrm{m}/\mathrm{s}^2\right)}$$

$$Isp = 2{,}000\mathrm{sec}$$



# Helium, near 100% gas utilization

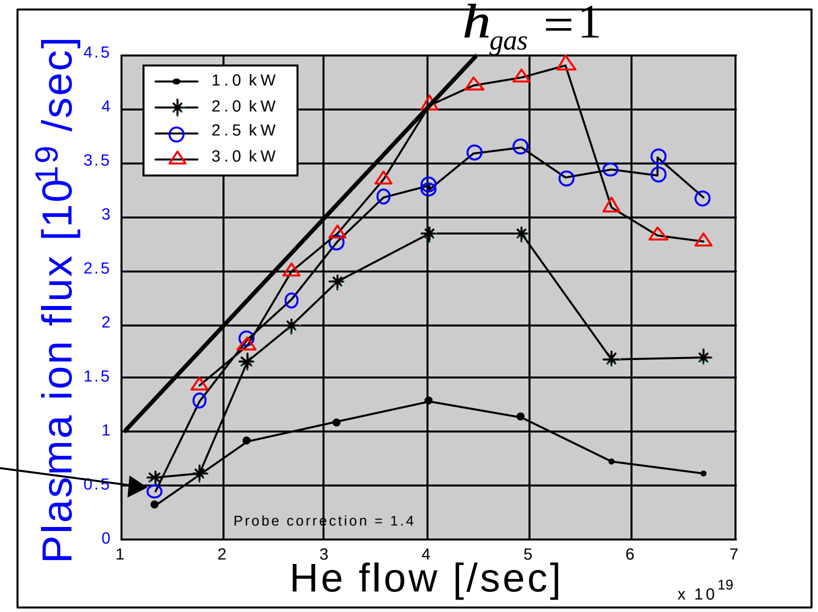
**Visible color change, plasma flux measurement and elevated electron temperature confirm neutral gas depletion.**

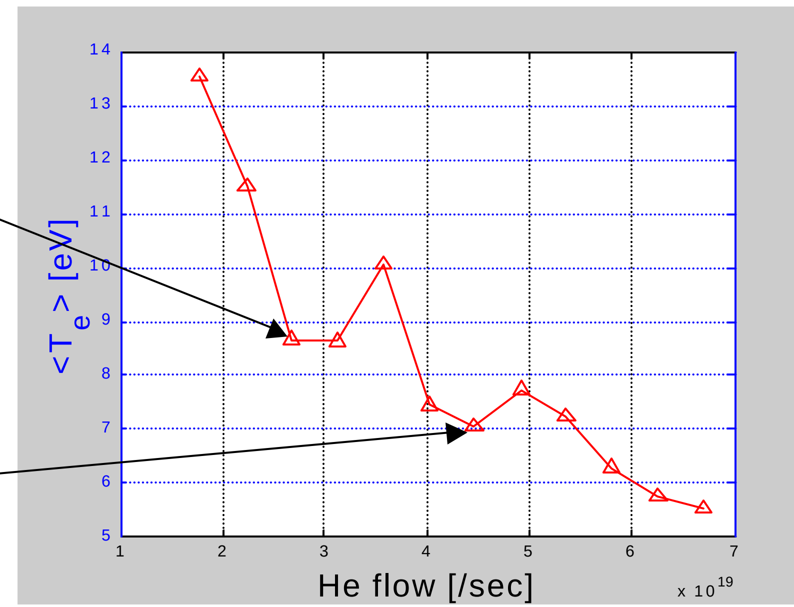



**30 sccm**
**shutter 1/26**

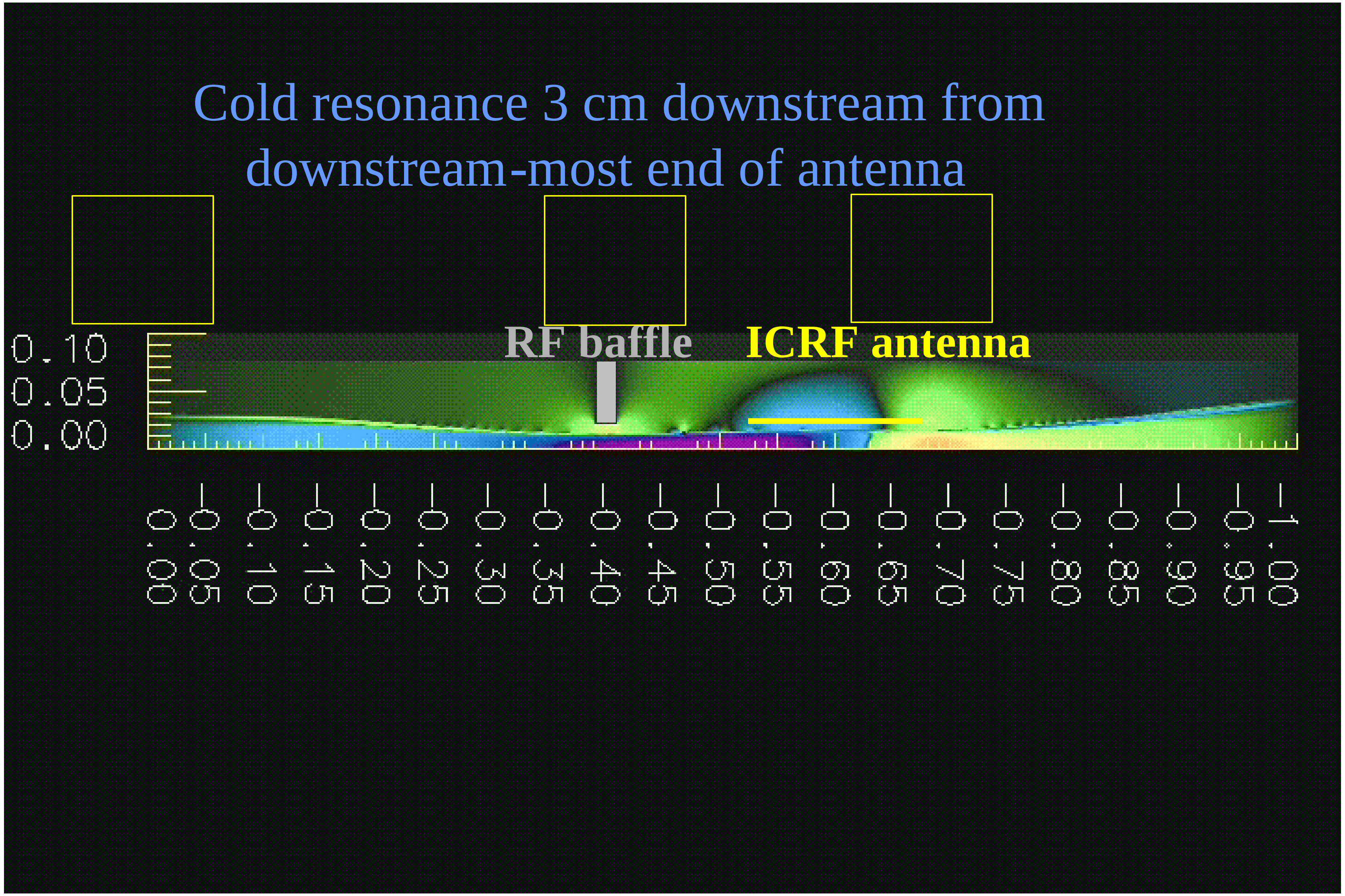
**50 sccm**
**Shutter 1/30**

**100 sccm**
**Shutter 1/75**

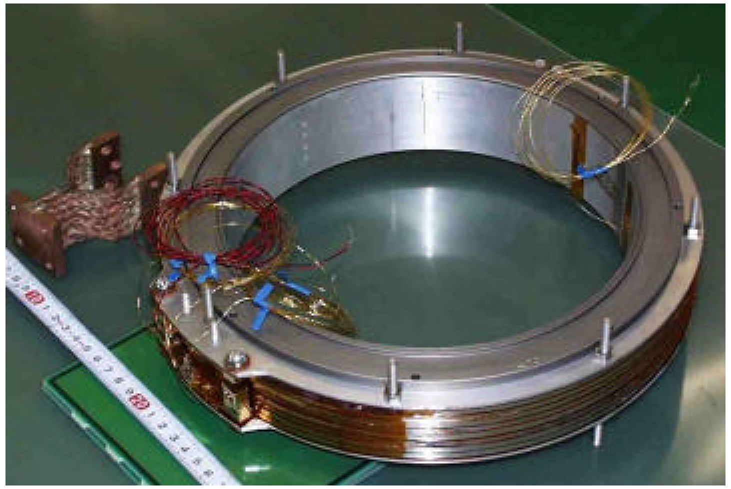


# $E^{+}$ time evolution

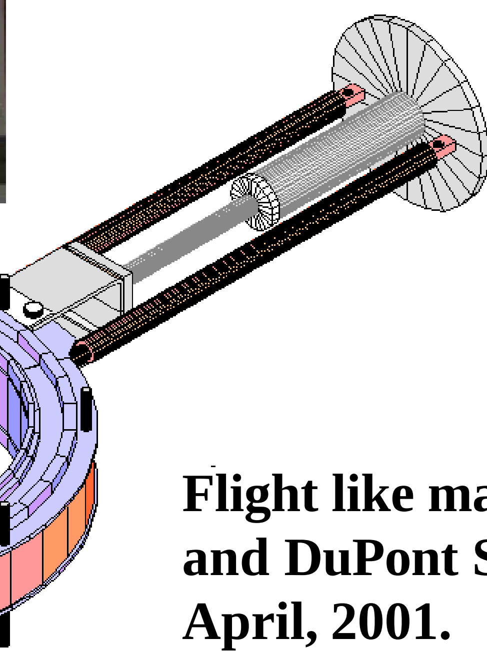


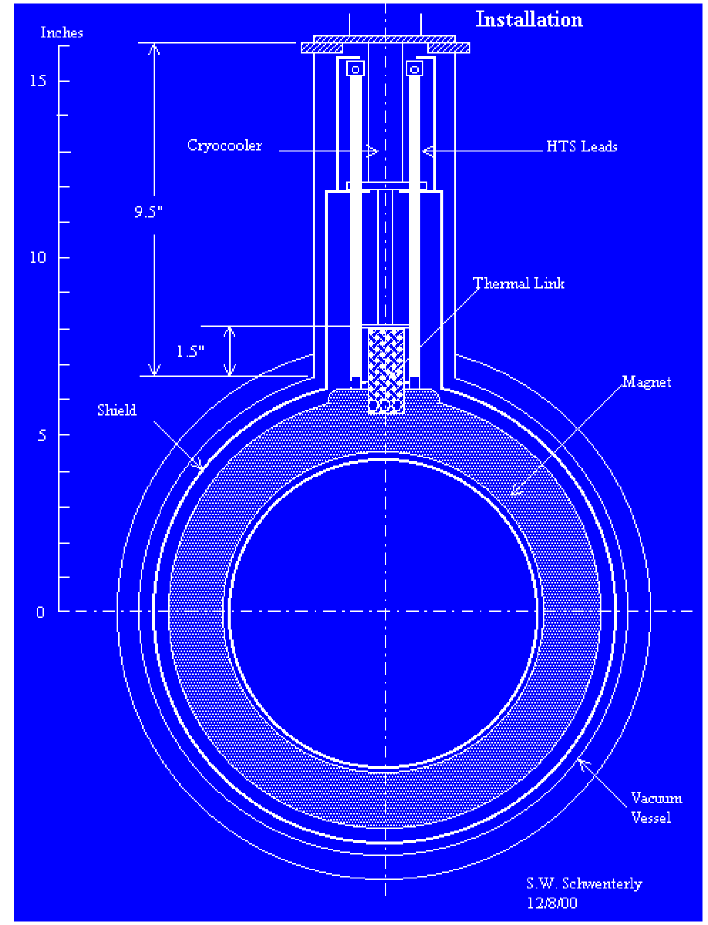
# Developed new superconducting magnet technology



**Material:**

**BSCCO 2223 at $40^{o}K$**

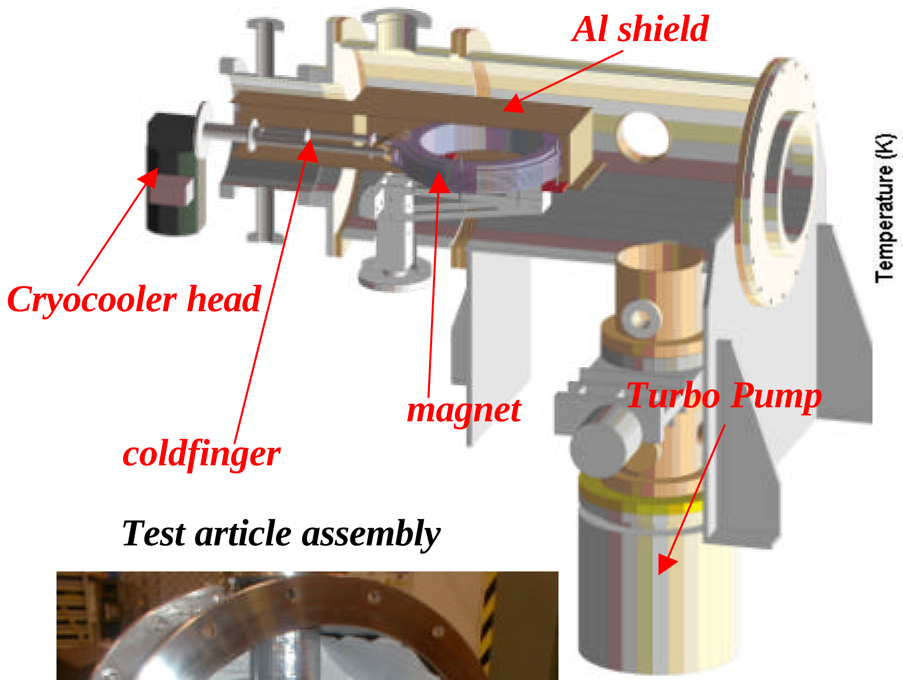




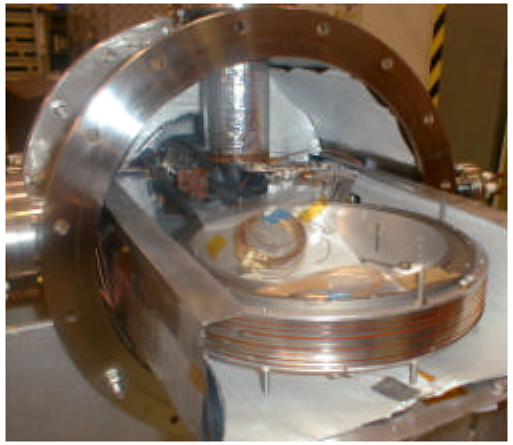

**Flight like magnet designed by NASA/ORNL and DuPont Superconductivity Inc. Delivered April, 2001.**

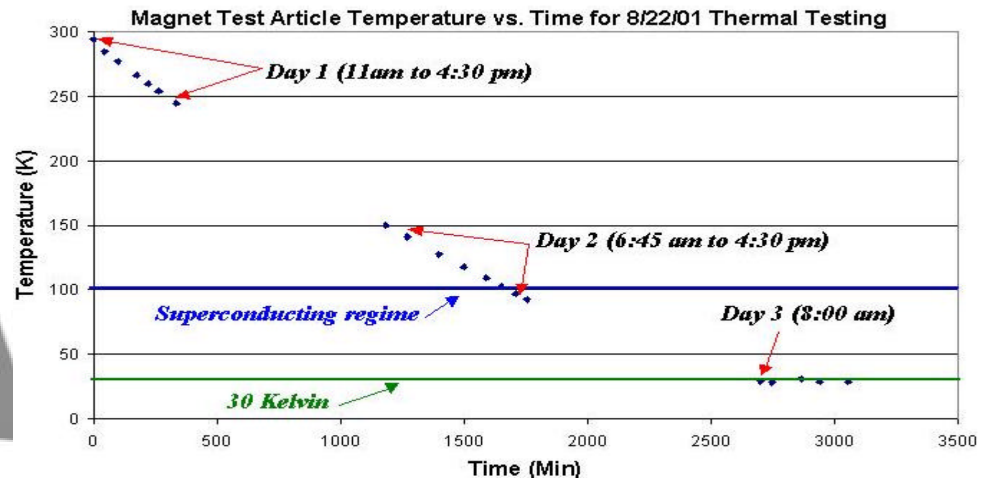
# Advanced Superconducting Magnet Testing

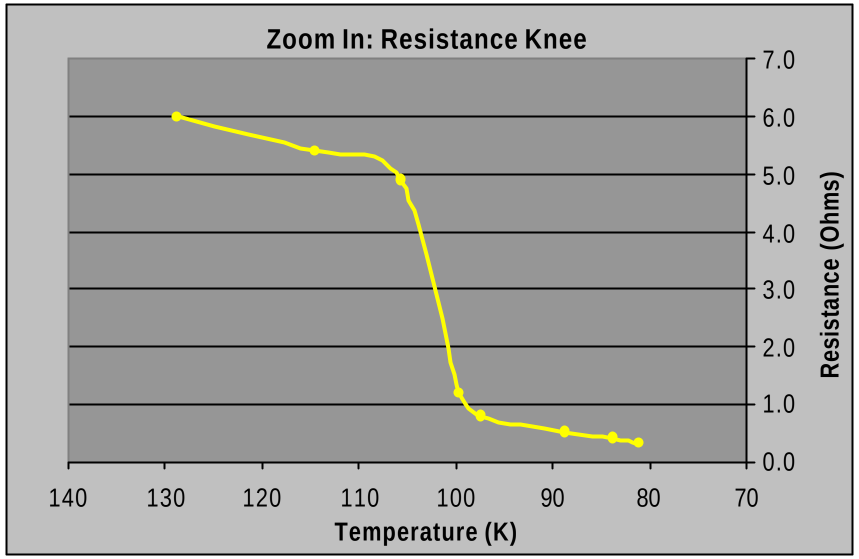
*August 9th 2002: ASPL demonstrated high temperature superconductivity by cooling the BSCCO 2223 (flight-like) magnet below critical temperature and observing the transition to zero resistance at about 100 ⁰ Kelvin.*




*Test article assembly*

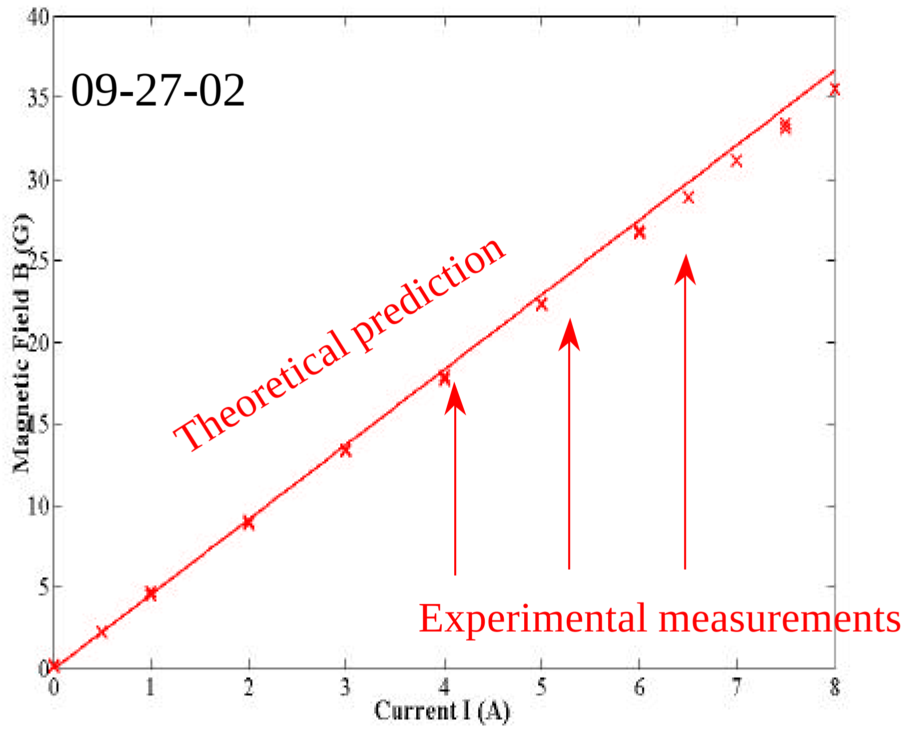


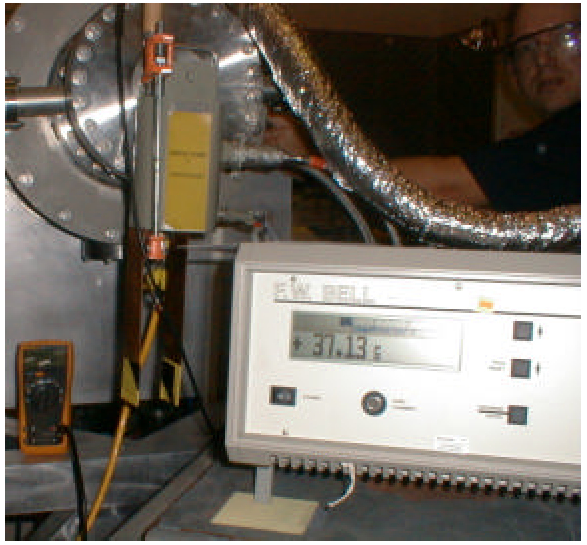


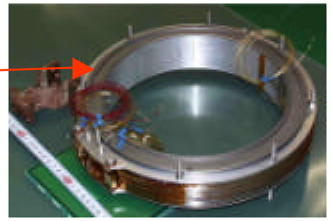
# Measured field tracks prediction very well

- *Magnet was operated on September 24 and 27, 2002 with up to 8 amps.*
- *Expected magnetic field strength was measured*
- *Temperature was stable during testing*
- *Maximum current tested so far is 79 amps, goal is 105 amps*
- *Cryocooler availability is pacing item*

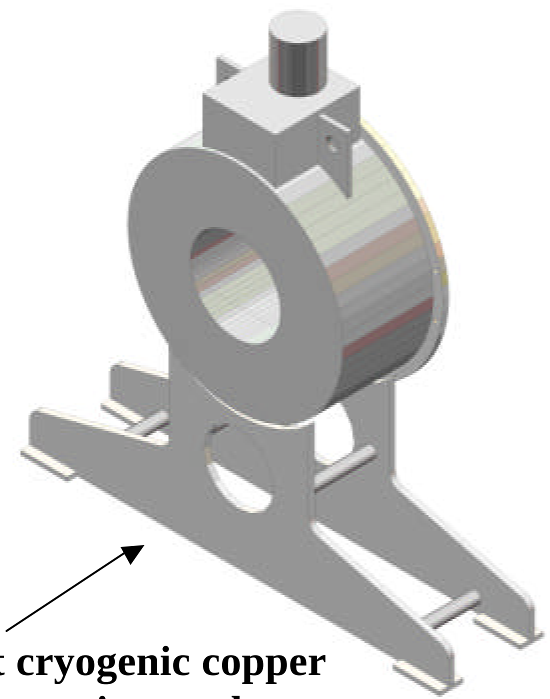


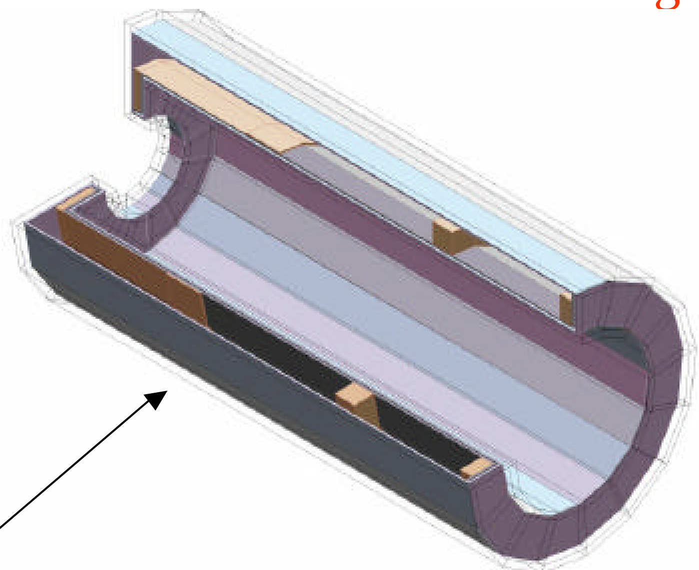
# New magnet brings dramatic mass reduction

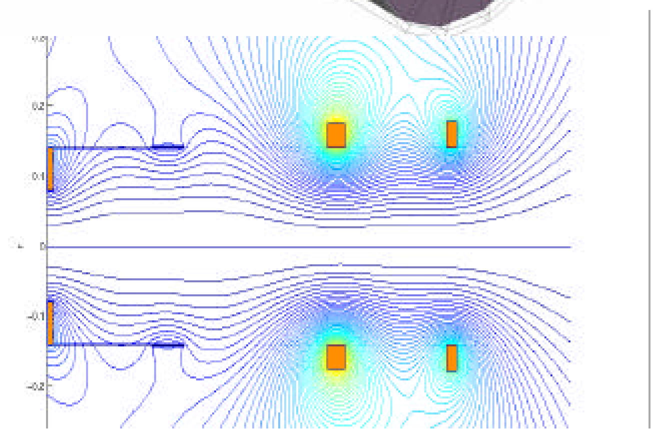


**New high-temperature superconducting magnet**
~ 5 kg



**Current cryogenic copper magnet in stand**
~ 150 kg

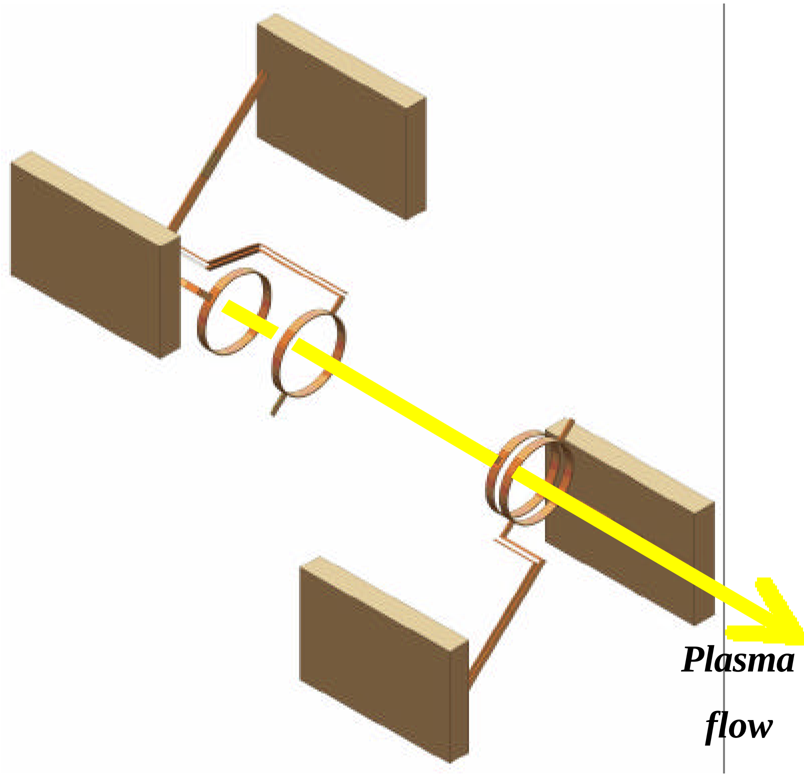


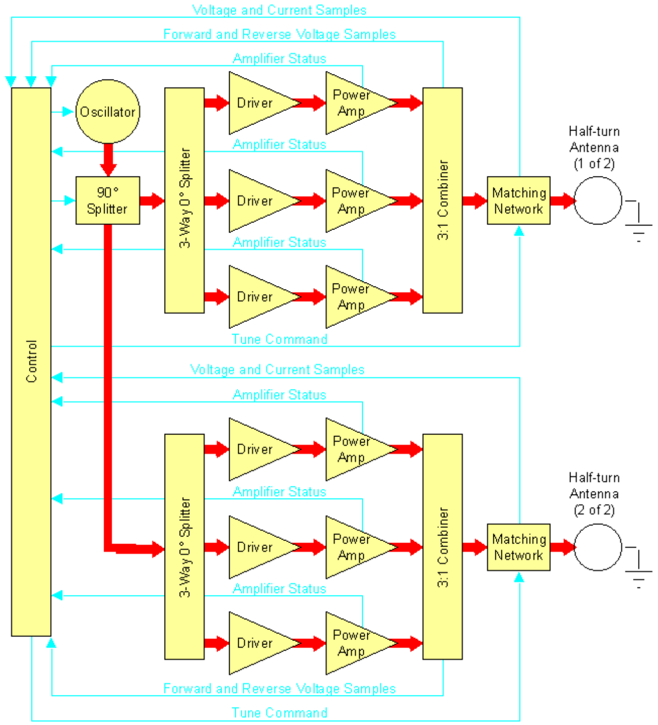


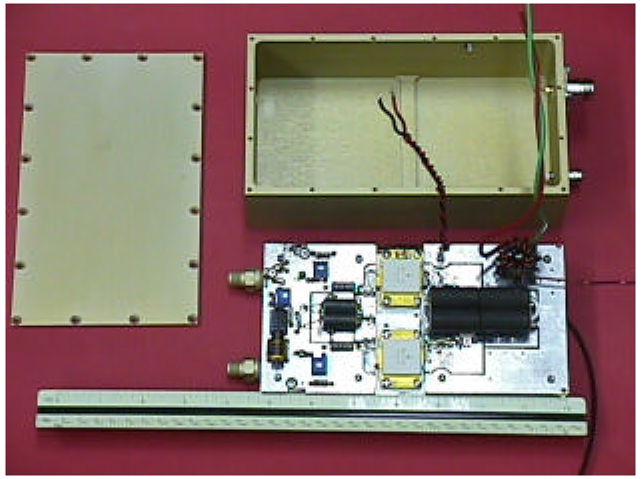
**Flight Experiment Magnet Assembly** ~ 20 kg
Cutaway view of magnet coils, spool, thermal shield, and multi-layer insulation. Magnetic field contour is shown at right.

# Solid state RF system design

- *Design draws from ORNL expertise in RF heating of fusion plasmas.*
- *System architecture is robust and failure tolerant.*
- *Prototype hardware has been built and is undergoing testing.*

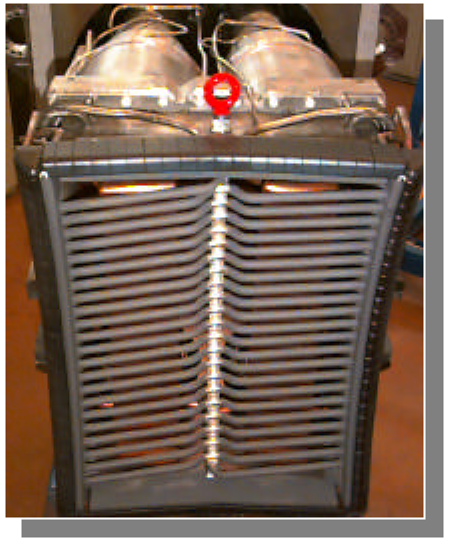


# Collaboration with DOE Labs

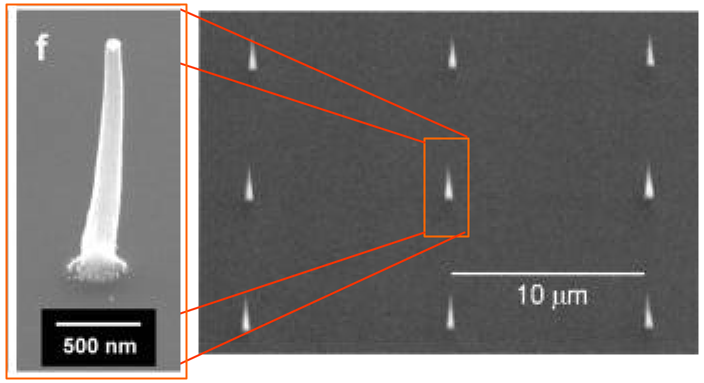
*The DOE laboratories have gathered a lot of experience through decades of research in magnetic confinement fusion.*



**Multi Megawatt antennas for plasma heating are already operational**

**2.8 MWatt RF tube technology such as this one can be adapted for space operations**


**Carbon nanotube technology for cold, field emission cathodes will increase efficiency**

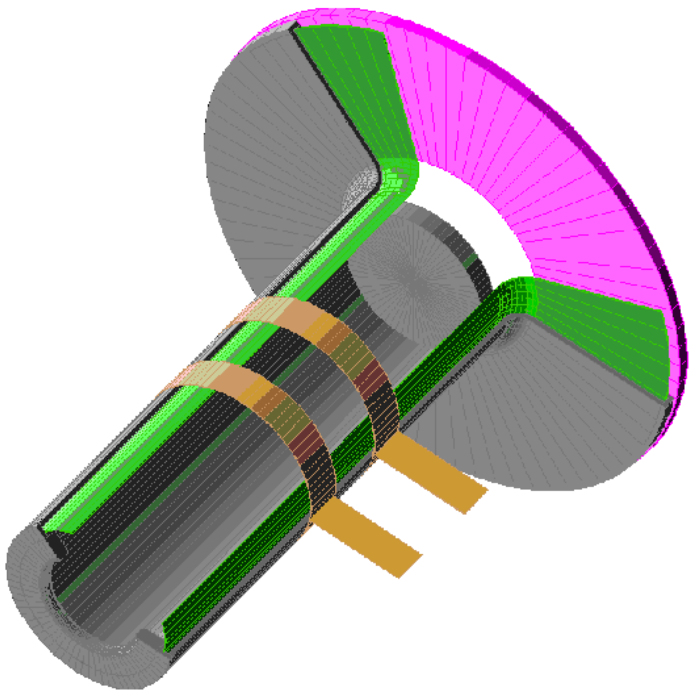


# We are developing advanced thermal strategies

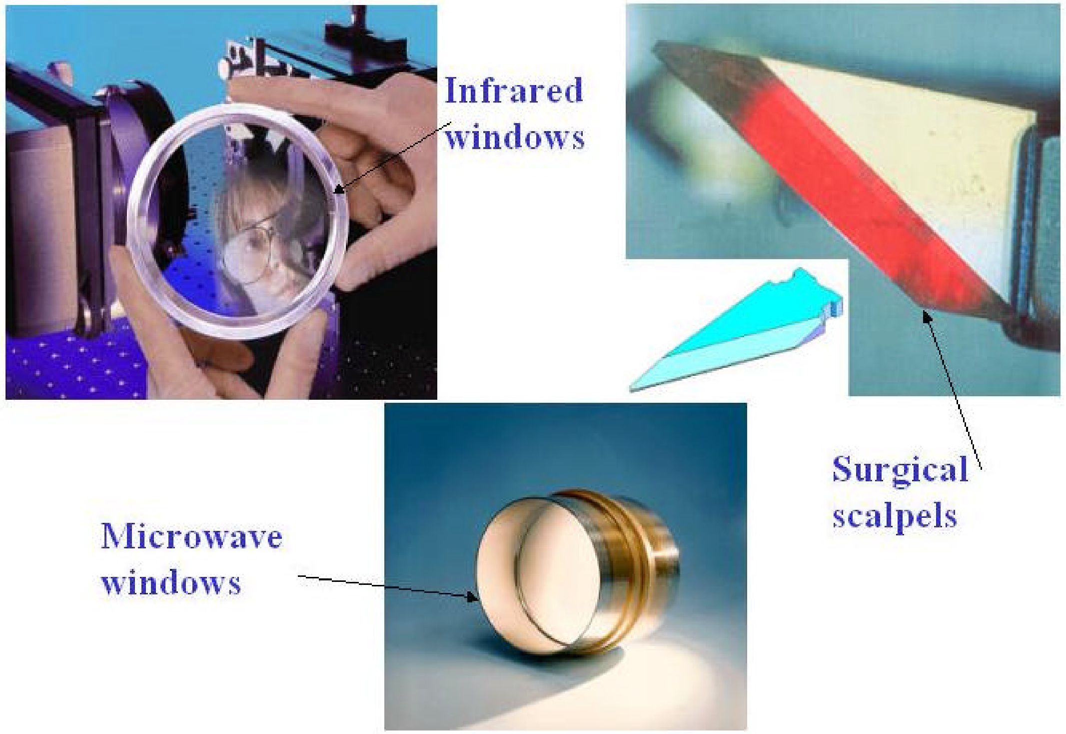
- Remove heat nearest its source at high temperature

Integrated heat pipes and Cryocooler technology (working with GSFC)

Advanced materials (working with industry)



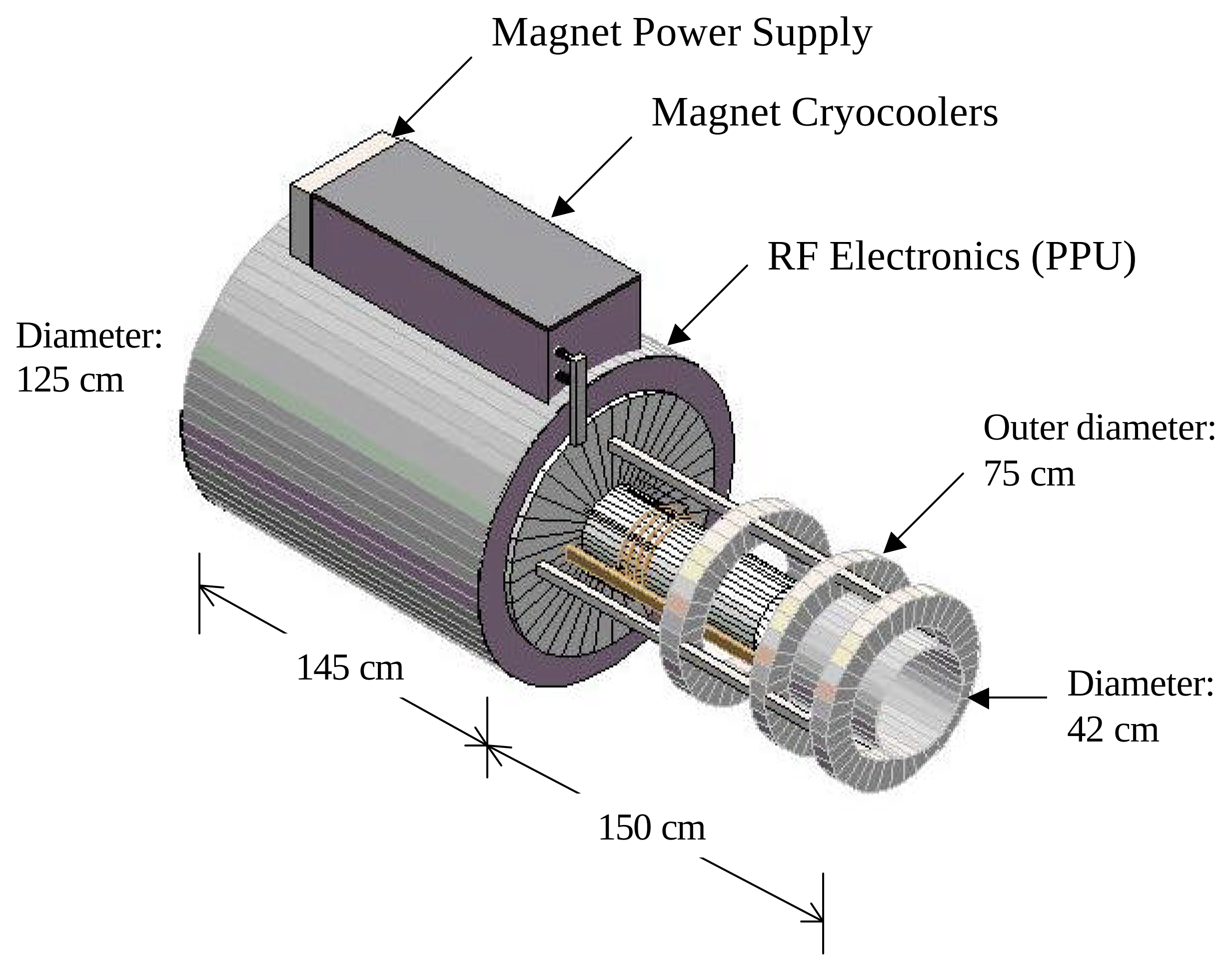
**Helicon heat pipe**




**CVD Diamond Technology from ManSat Inc.**

# Completed Point Design for One MWatt Engine

## Engine, PPU and Cryocoolers

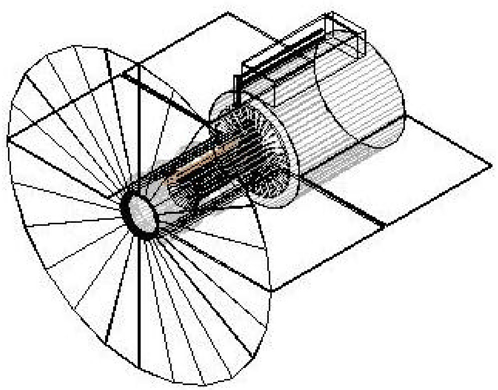


# Conservative mass estimate very attractive

| Engine | Mass (kg) | Dimensions (cm) |
|---|---|---|
| Propellant controller | 5 | 30 x 20 x 10 |
| Engine tube | 5.4 | 55 x 42 dia .4 thick |
| Helicon tube | 8.5 | 85 x 30 dia .3 thick |
| Helicon antenna | 0.27 | 1.3 x 30 dia .2 thick |
| ICRF antenna | 1.2 | 4.5 x 20 dia .2 thick |
| Helicon transmission lines | 0.2 | 2 x.5 x 75 |
| ICRF transmission lines | 0.4 | 2 x .5 x 150 |
| Magnet power supply | 10 | 45 x 30 x 10 |
| Magnet cryocoolers (3) | 55 | 115 x 45 x 30 |
| Magnet loop heat pipe | 3 | 300 x 3 |
| Cryocooler radiator | 2.2 | 22 x 115 |
| Magnet coils (3) | 70 | 55 ID 60 OD 5 thick |
| Magnet support and insulation | 10.5 | |
| Instrumentation | 5 | |
| System controller | 9 | 26 x 50 x 9 |
| Engine radiator | 124 | 3.64 m dia + 2x(1.38 x 1.5) |
| Engine support structure | 31 | |
| Engine Total | 340.67 | |

| Power Processing Unit | Mass (kg) | Dimensions (cm) |
|---|---|---|
| RF power distribution | 150 | 2x(140 x 28 x 10) |
| Helicon oscillator (4) | 4.52 | 4x(15 x 8 x 5) |
| Helicon driver (4) | 5.2 | 4x(20 x 20 x 8) |
| Helicon power amplifier (4) | 144.8 | 4x(106 x 23 dia) |
| Helicon tuned line matcher (4) | 21.6 | 4x(143 x 25 dia) |
| Shorted stub matcher (4) | 21.6 | 4x(143 x 25 dia) |
| ICRF oscillator (4) | 4.52 | 4x(15 x 8 x 5) |
| ICRF driver (4) | 60 | 4x(21 x 21 x 8) |
| ICRF power amplifier (4) | 160 | 4x(108 x 23 x 8) |
| ICRF matching network (4) | 100 | 4x(54 x 12 x 4) |
| ICRF Antenna tuner (4) | 120 | 4x(54 x 12 x 5) |
| PPU radiator | 45 | 2x(1.2 x 1.45) + 2.8 m2 |
| PPU structure and fittings | 84 | |
| PPU Total | 921.24 | |

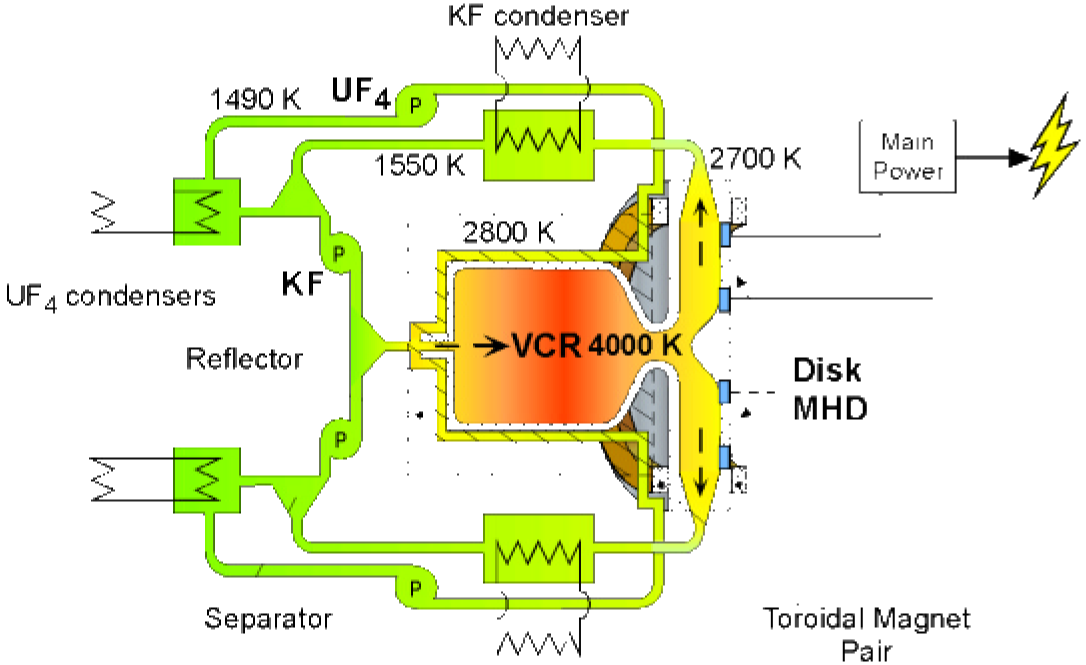
Radiator Panel Mass: One-sided: 4.9 $kg/m^2$ Two-sided: 8.9 $kg/m^2$
Antenna sizing based on 5 $MW/m^2$



## Mass Estimate for 1 MW Point Design

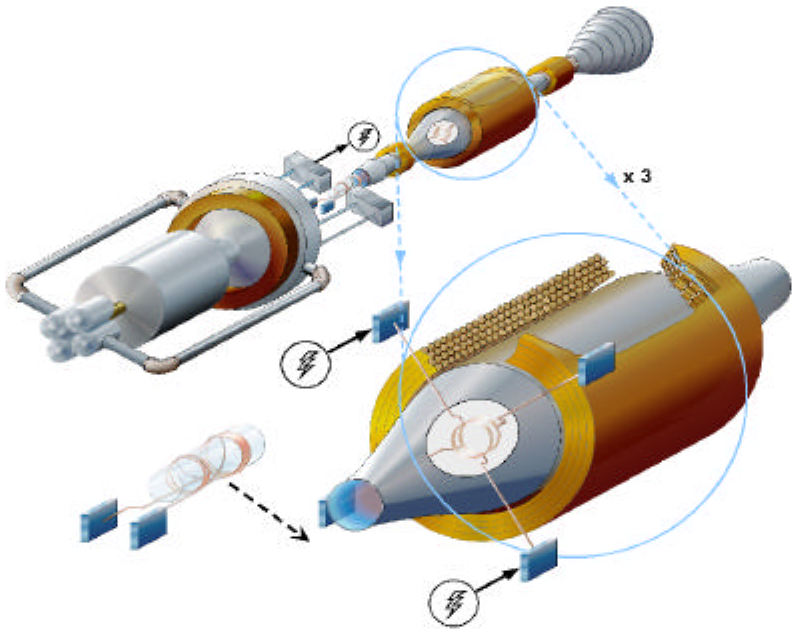
| | | |
|---|---|---|
| Engine: | 341 kg | $\alpha$ = 0.3 kg/kWe |
| PPU: | 921 kg | $\alpha$ = 0.9 kg/kWe |
| Total System: | 1262 kg | $\alpha$ = 1.26 kg/kWe |

# Development of Multi MW Nuclear Power Systems



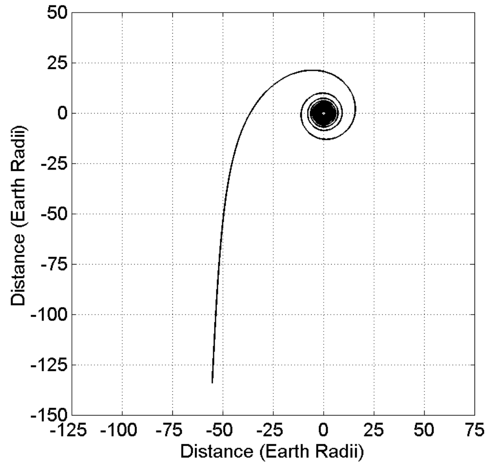

**Vapor Core Reactor with MHD power conversion**

**VASIMR configuration with Vapor Core Reactor System**

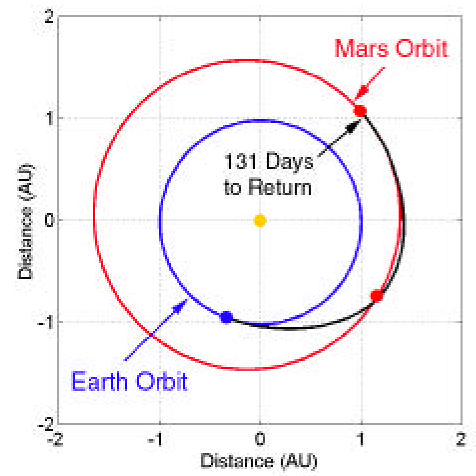



**Prof. Samim Anghaie, Director, Innovative Nuclear Space Power and Propulsion Institute, INSPI; University of Florida, Gainesville.**

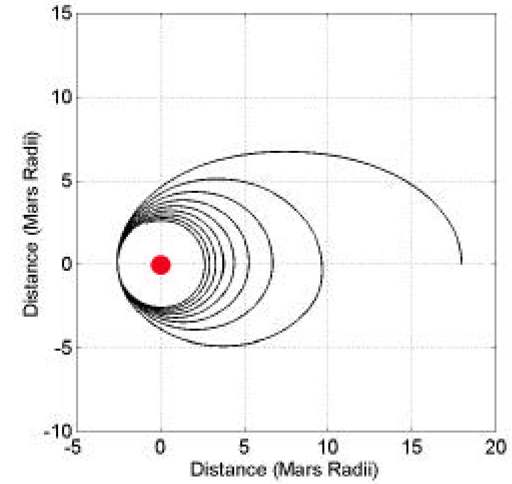
# Fast (115day) Mars Mission Architecture



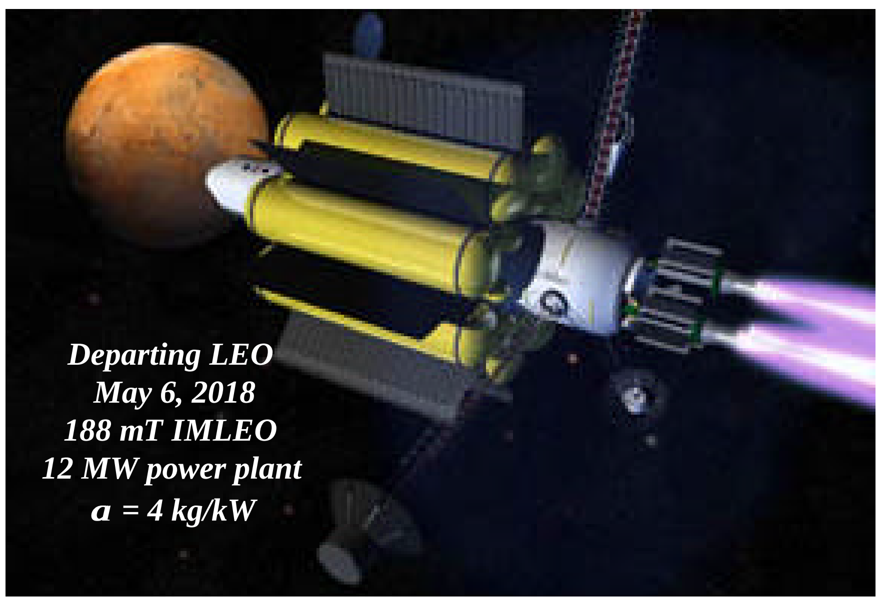

*High thrust*
*Earth spiral (30days)*

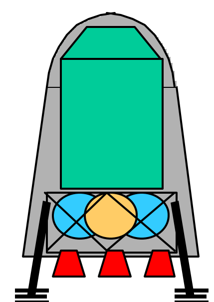



*Heliocentric*
*Trajectory(85days)*

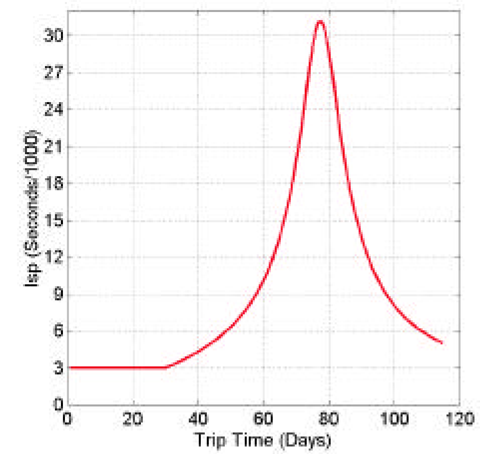



*Robotic Mars orbit*
*insertion*



*Crew Lander*
*(60.8 mT Payload)*
*31.0 mT Habitat*
*13.5 mT Aeroshell*
*16.3 mT Descent System*




*Isp profile for*
*piloted segment*

# Higher Power dramatically reduces trip time

200MW Earth to Mars Missions

$\alpha = 0.5$; Maximal $I_{sp} = 30{,}000$

Payload Mass 22 mT

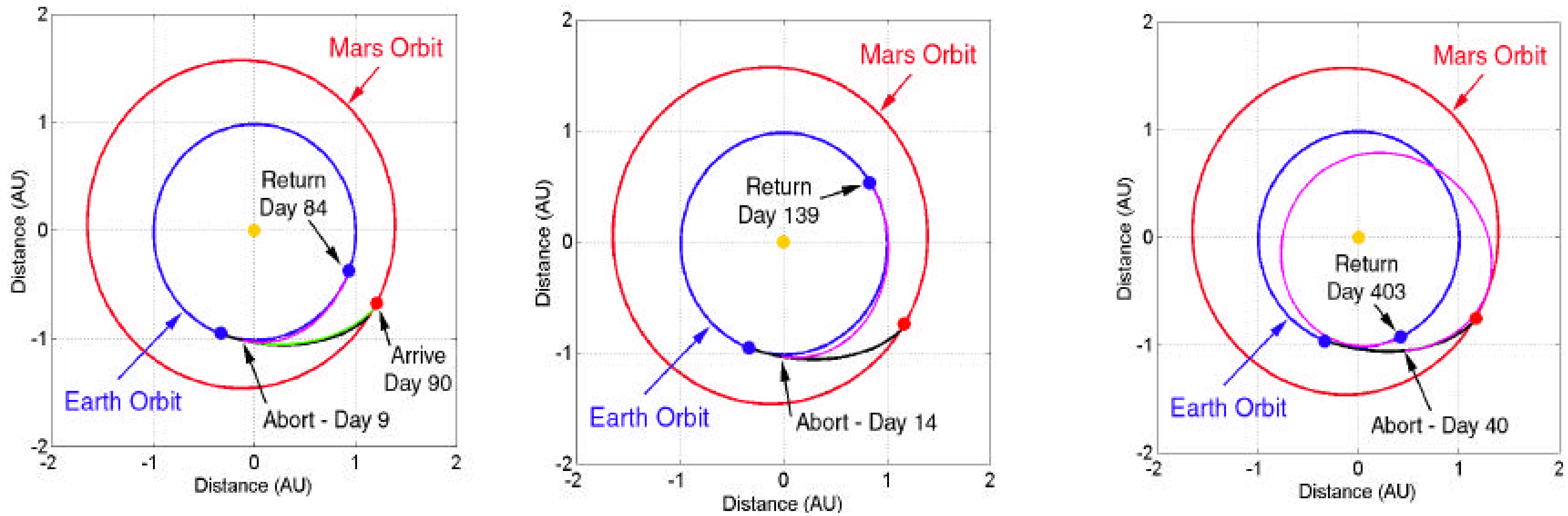
| Total Initial Mass (mT) | Spiraling around Earth fuel (mT) | time (days) | Heliocentric trajectory fuel (mT) | time (days) | Final relative velocity (km/s) | Total trip time (days) |
|---|---|---|---|---|---|---|
| | | | | | | |
| 600 | 180 | 7 | 298 | 34 | 0 | 41 |
| 350 | 117 | 5 | 111 | 42 | 0 | 47 |
| 250 | 88 | 4 | 40 | 49 | 0 | 53 |
| | | | | | | |
| 600 | 152 | 8 | 324 | 31 | 6.8 | 39 |

# VASIMR enables contingency abort capability

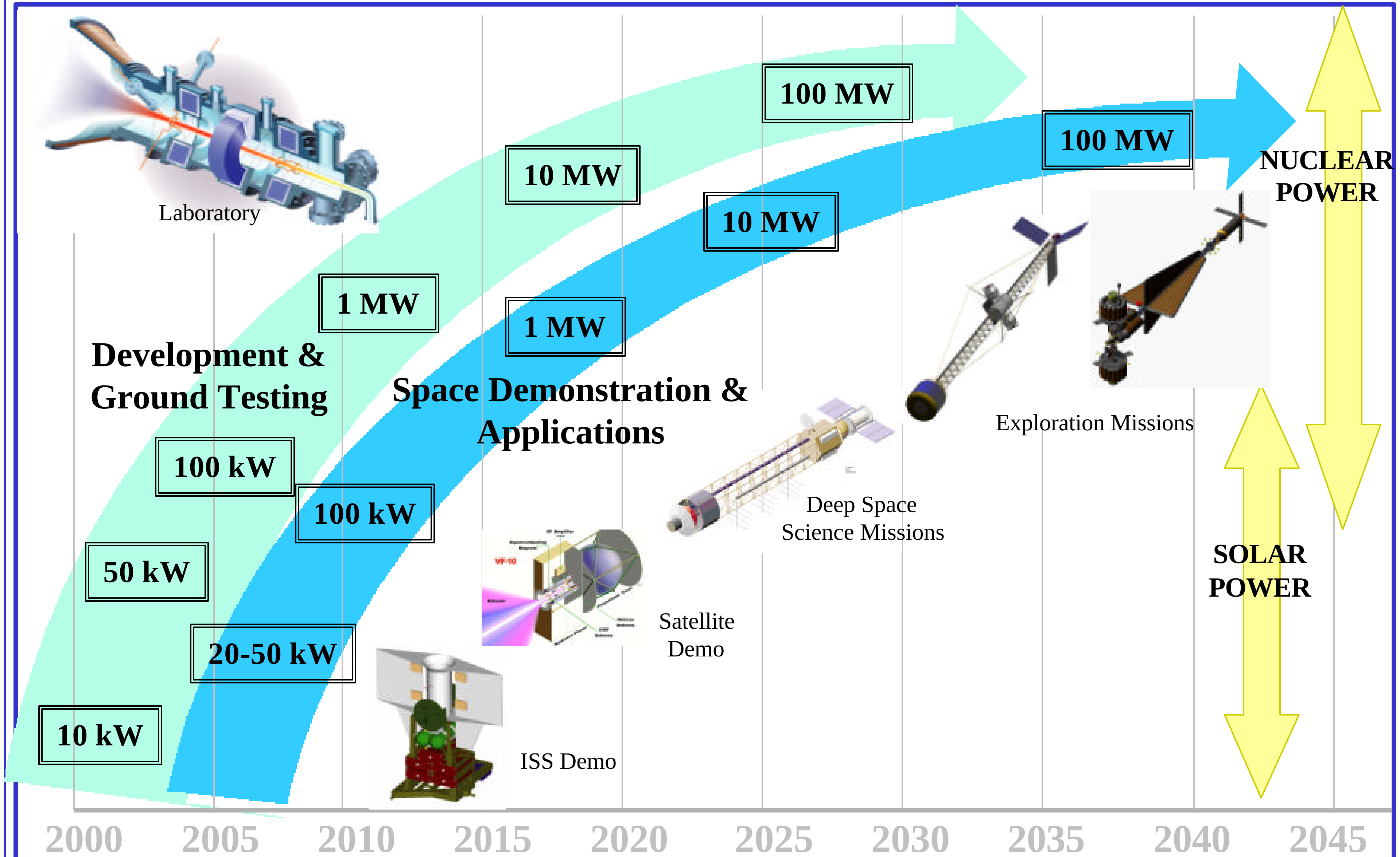
***With variable $I_{sp}$, operational flexibility is increased in the event of loss of propellant or other system failures***

Aborts due to loss of propellant

Aborts deep into the mission due to non propulsion system failures



# Development Roadmap




**A variety of demonstrations and applications of increasing capability are envisioned**

# Main DOE and University Collaborators

- **Oak Ridge National Laboratory, Fusion Energy Division**: Dr. Wally Baity, RF systems
  - Dr. Mark Carter, RF systems, plasma theory, magnetic system design
  - Dr. Rick Goulding, experimental plasma generation and heating
  - Dr. William Schwenterly, superconducting magnet design
- **Los Alamos National Laboratory**: Dr. Patrick Colestock, wave physics and simulation
  - Dr. Max Light, helicon physics and wave diagnostics
- **University of Alabama, Huntsville: Dept of Physics:** Dr. James Miller
  - Mr. Greg Chavers, plume energy and momentum measurements (Also, from NASA, MSFC)
- **Australian National University: Plasma Research Laboratory:** Dr. Roderick Boswell, Helicon design and wave physics
  - Dr. Christine Charles, magnetized plume physics
  - Mr. Orson Sutherland, helicon physics
- **University of Texas, Austin, Fusion Research Center**: Dr. Roger Bengtson, experimental plasma physics and diagnostics
  - Dr. Boris Breizman, plasma theory and system scaling
  - Dr. Alexei Arefiev, plasma theory and system scaling
  - Dr. Cesar Ocampo, Trajectory design and optimization
  - Mr. Christopher Rainieri, trajectory design and optimization
- **Costa Rica Center for High Technology**
  - Dr. Jorge Andrés Díaz, mass spectroscopy and recombination chemistry
- **University of Florida at Gainesville, Inovative Space Nuclear Power Institute**
  - Dr. Samim Anghaie (Director), Space Nuclear Reactor Design
- **Rice University, Dept. of Physics and Astronomy**: Dr. Anthony Chan, plasma theory
  - Dr. Carter Kittrell, experimental plasma spectroscopy
  - Dr. Timothy Glover, plasma diagnostics, optical interferometry
- **University of Houston, Dept. of Physics**:
  - Dr. Edgar Bering, experimental plasma physics and ion diagnostics
- **Alfven Laboratory, Swedish Royal Institute of Technology:**
  - Dr. Nils Brenning, RF wave physics (experiment)
  - Dr. Einar Tenfors, wave physics (theory)
- **MIT, Plasma Science and Fusion Center**: Dr. Kim Molvig, Plasma theory and simulation
  - Dr. Oleg Batischev, plasma non-linear theory and simulation
- **University of Michigan**: Dr. Brian Gilchrist
  - Mr. Christopher Davis, plasma interferometry

# VASIMR Workshop 2002

**International**
- National Center for High Technology (Costa Rica)
- Australian National University
- Alfvén Laboratory (Sweden)

**Government**
- **NASA:** JSC, MSFC, GSFC, LaRC
- **DOE:** ORNL, LANL

**Industry**
- Muñiz Eng.
- Barrios Eng.
- Lockheed Martin
- DuPont
- SAIC
- ManSat
- Cyrospace

**Strong participation of students at both graduate and undergraduate levels**

**Academia**
- UT-Austin
- Rice U
- U of Maryland
- U of Houston
- MIT
- U Florida
- U Michigan
- UAH
- Princeton